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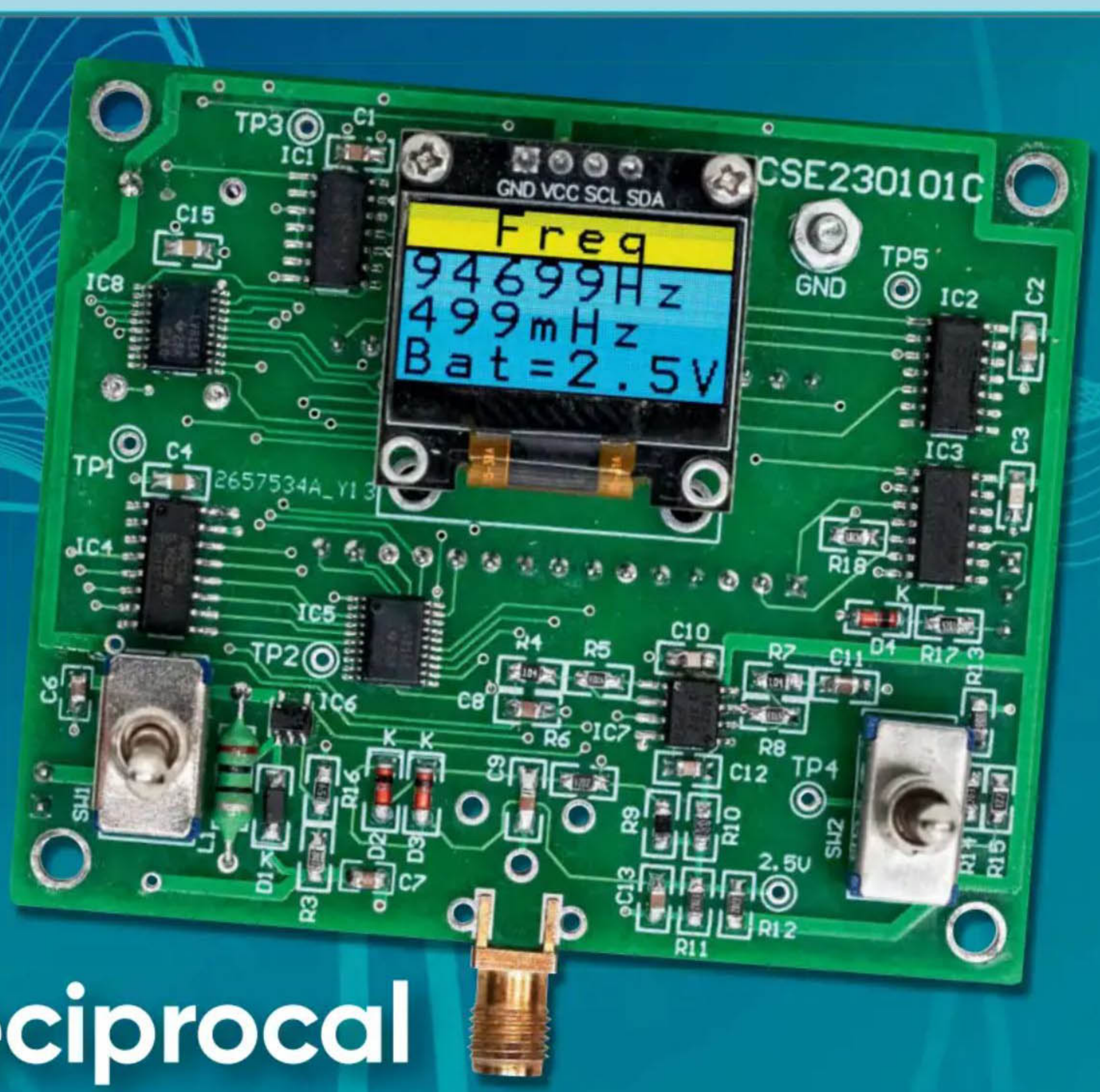
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Bat=2.5V

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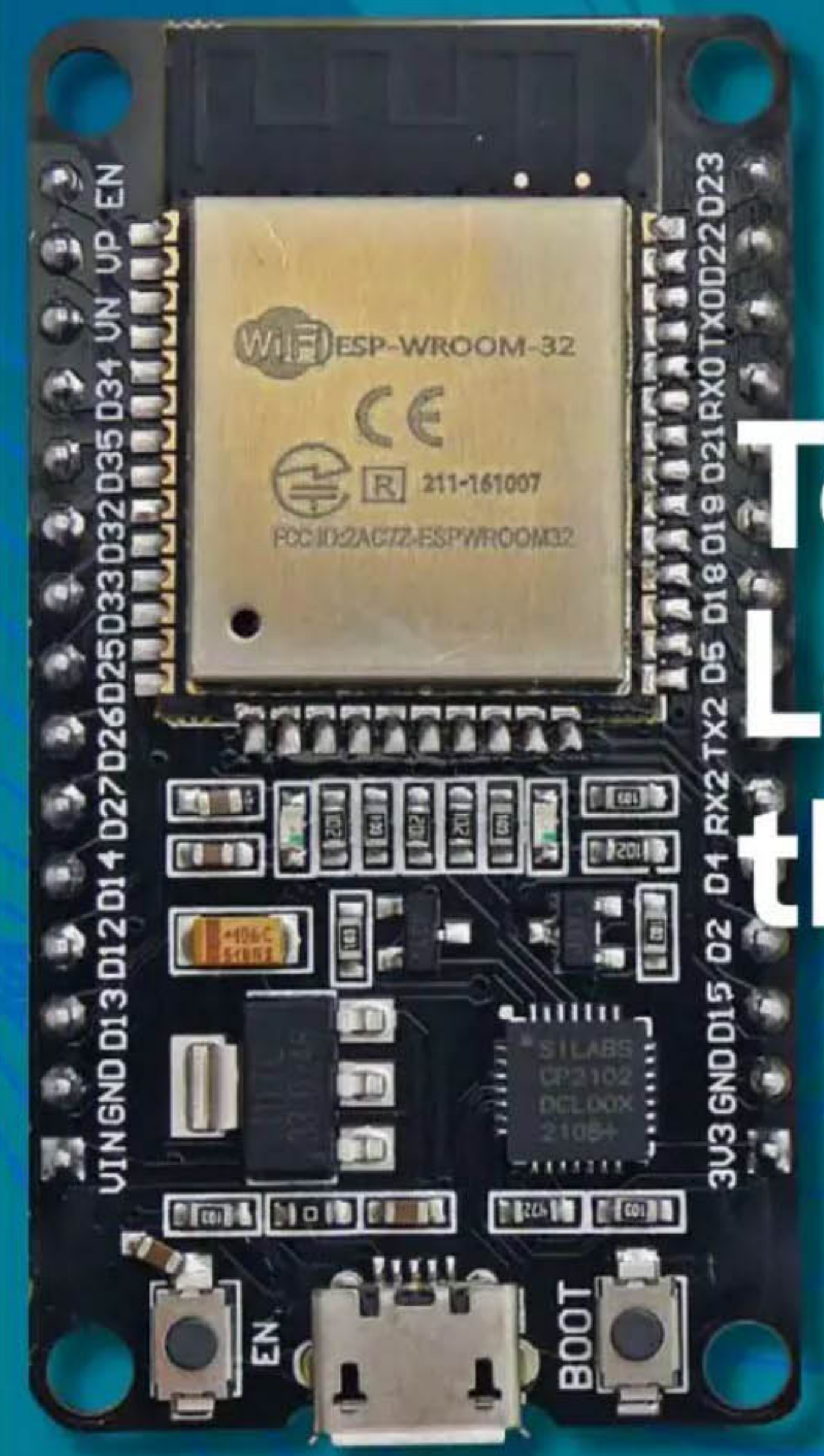
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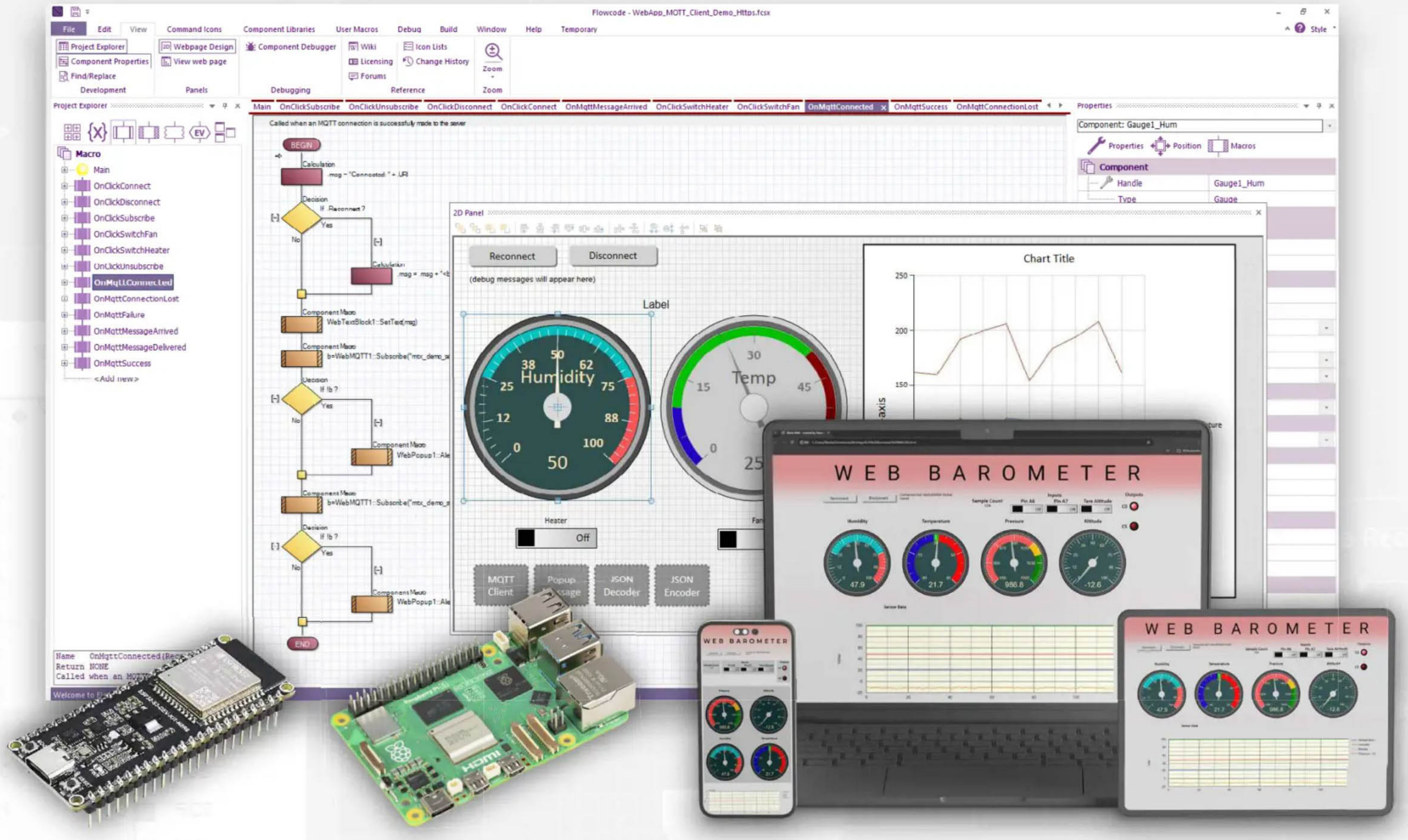
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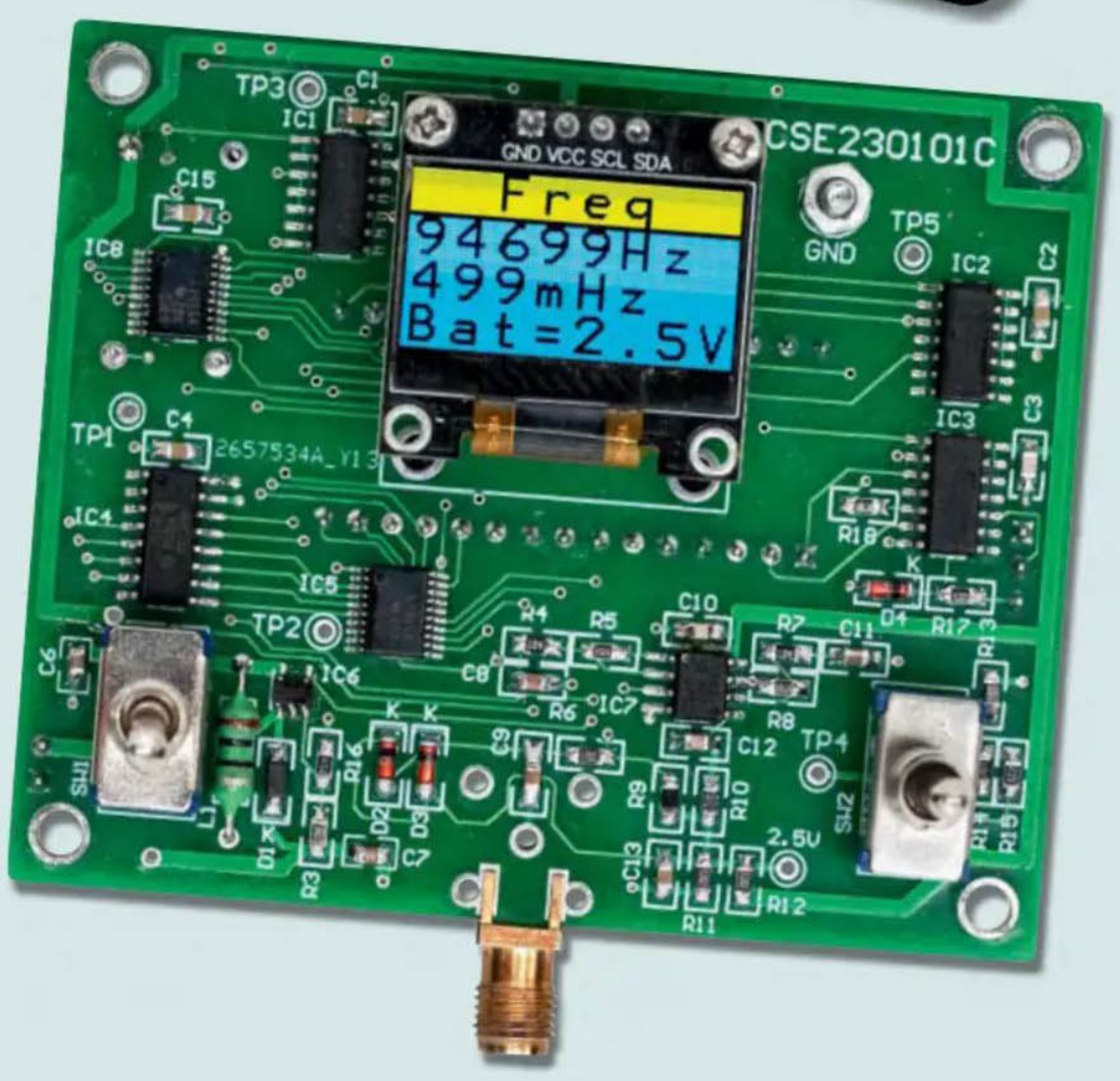

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Pi Pico-based Thermal Camera by Kenneth Horton 17
A thermal infrared camera measures hot or cold spots compared to the surrounding area – useful for diagnosing hot spots in electronic circuits, which may indicate a failing component. They can be pricey, but not this one, a DIY version that's easy to build.

Dynamic NFC Tag by Tim Blythman 22
The availability of dynamic NFC tags means you can now easily create your own custom NFC/RFID Tags. This article explains how to program NFC chips that can be used as smart business cards and more.

Reciprocal Frequency Counter by Charles Kosina 30
A traditional frequency counter samples over a long period to get an accurate result. This one instead measures the average period and calculates the inverse, so it only needs to monitor a few pulses to get a precise reading. It's useful up to about 10MHz.

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The August 2024 issue of *Practical Electronics* will be published on Thursday, 4 July 2024 – see page 72.

WIRELESS FOR THE WARRIOR

by LOUIS MEULSTEE

THE DEFINITIVE TECHNICAL HISTORY OF RADIO COMMUNICATION EQUIPMENT IN THE BRITISH ARMY

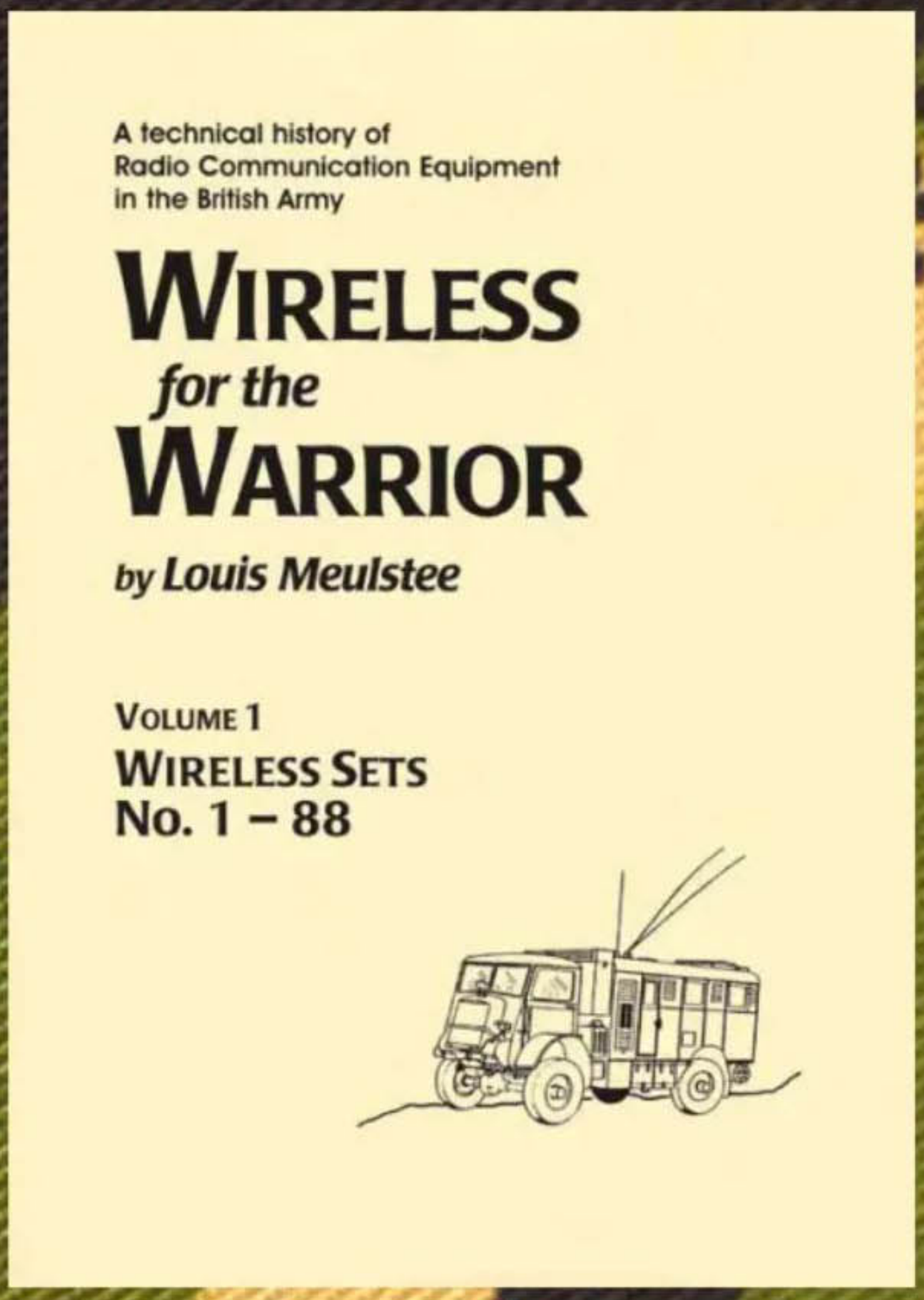
The *Wireless for the Warrior* books are a source of reference for the history and development of radio communication equipment used by the British Army from the very early days of wireless up to the 1960s.

The books are very detailed and include circuit diagrams, technical specifications and alignment data, technical development history, complete station lists and vehicle fitting instructions.

Volume 1 and *Volume 2* cover transmitters and transceivers used between 1932-1948. An era that starts with positive steps taken to formulate and develop a new series of wireless sets that offered great improvements over obsolete World War I pattern equipment. The other end of this timeframe saw the introduction of VHF FM and hermetically sealed equipment.

Volume 3 covers army receivers from 1932 to the late 1960s. The book not only describes receivers specifically designed for the British Army, but also the Royal Navy and RAF. Also covered: special receivers, direction finding receivers, Canadian and Australian Army receivers, commercial receivers adopted by the Army, and Army Welfare broadcast receivers.

Volume 4 covers clandestine, agent or 'spy' radio equipment, sets which were used by special forces, partisans, resistance, 'stay behind' organisations, Australian Coast Watchers and the diplomatic service. Plus, selected associated power sources, RDF and intercept receivers, bugs and radar beacons.



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in the British Army

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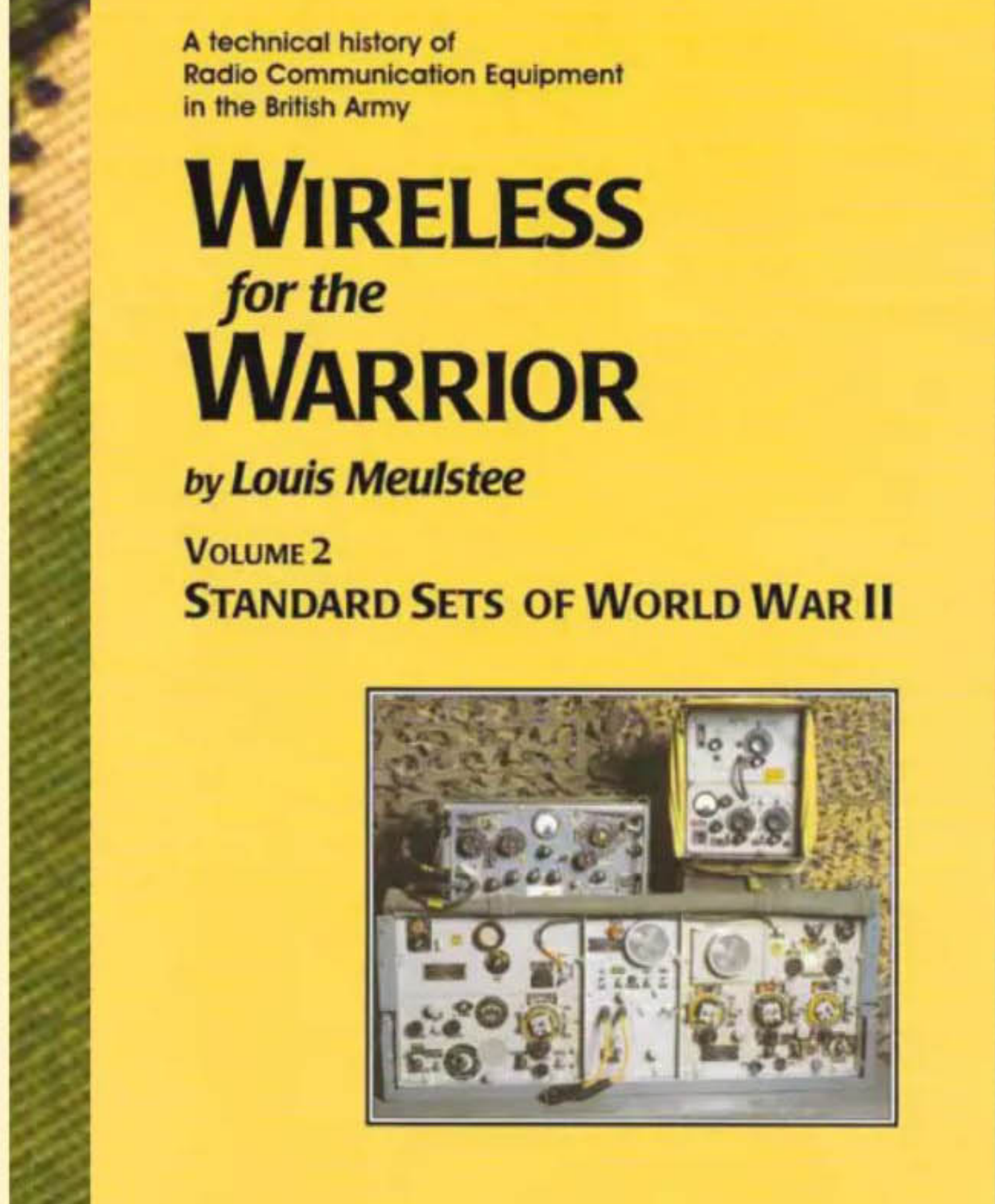

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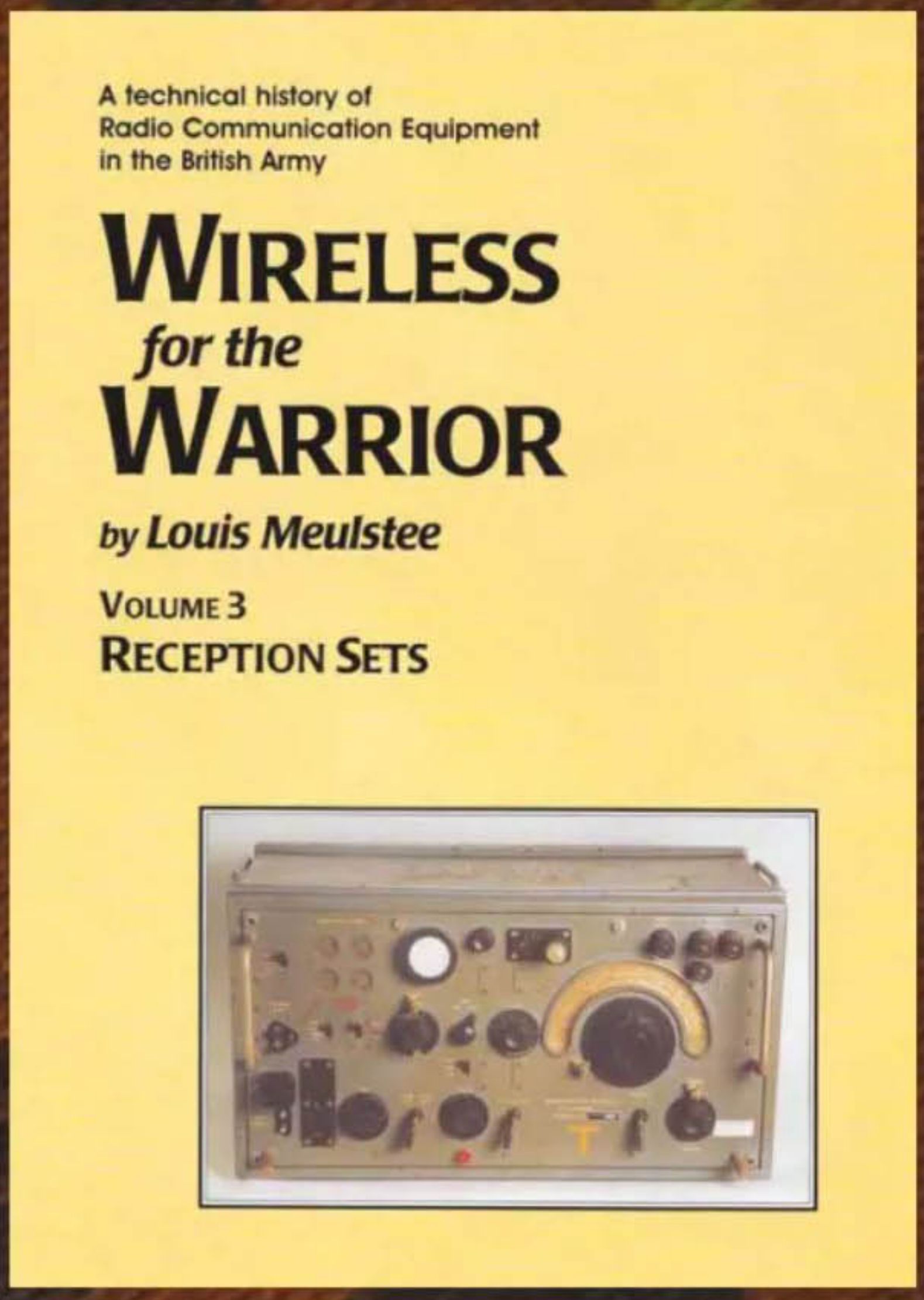

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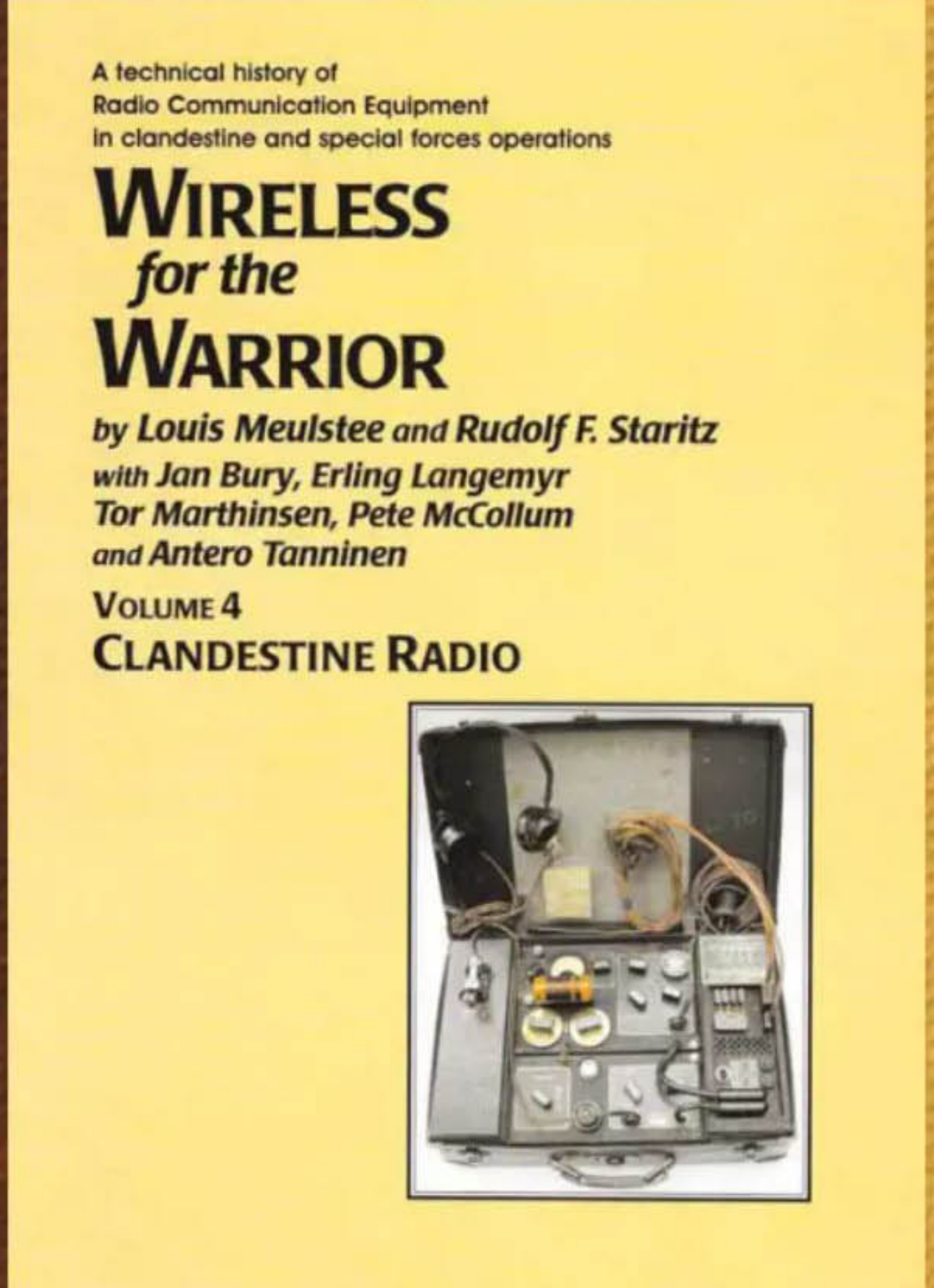

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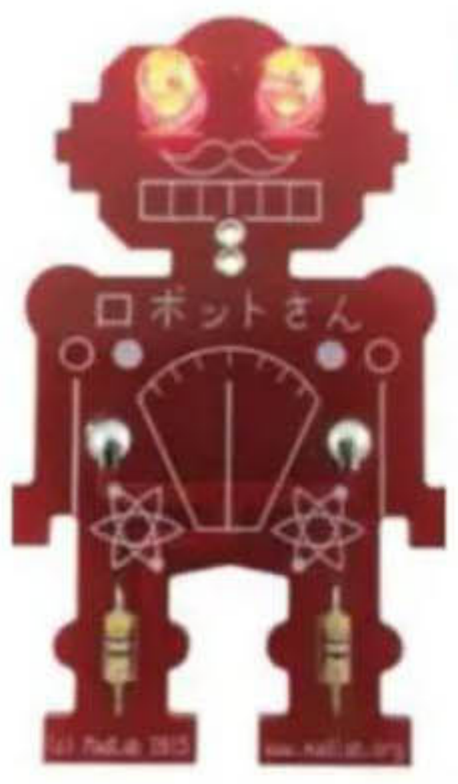

A fun, wearable electronic gadget that you can pin to your clothes. Easy to solder beginners kit. Two flashing bicolour LEDs resemble the eyes. 65 x 40 x 15 mm. CR2032 battery powered (not included).
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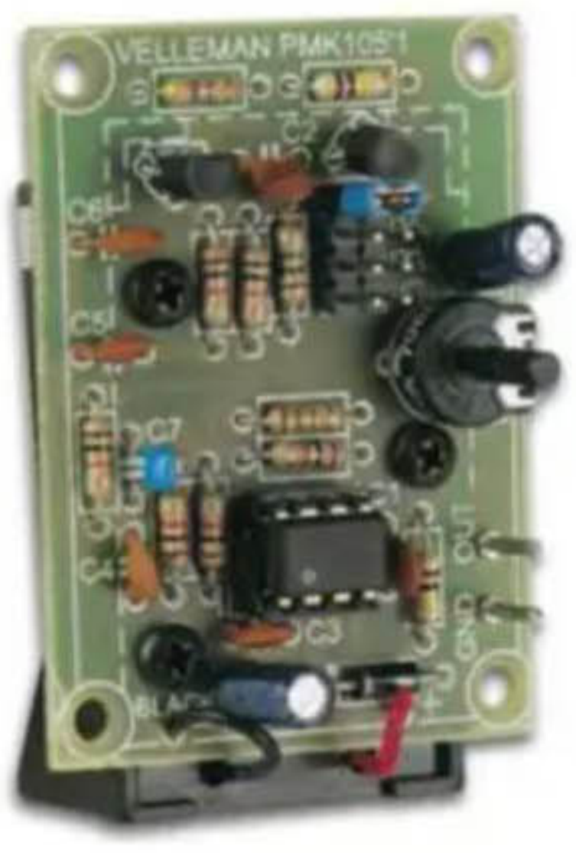

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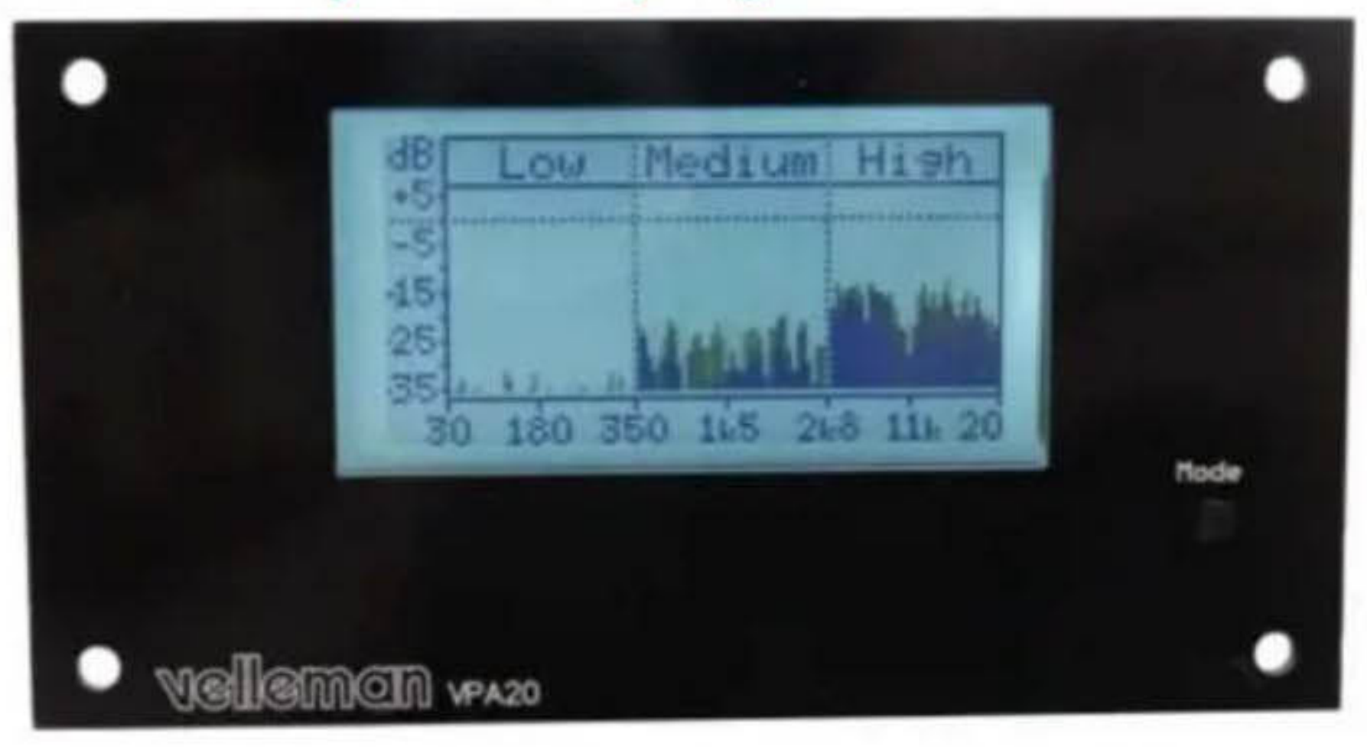

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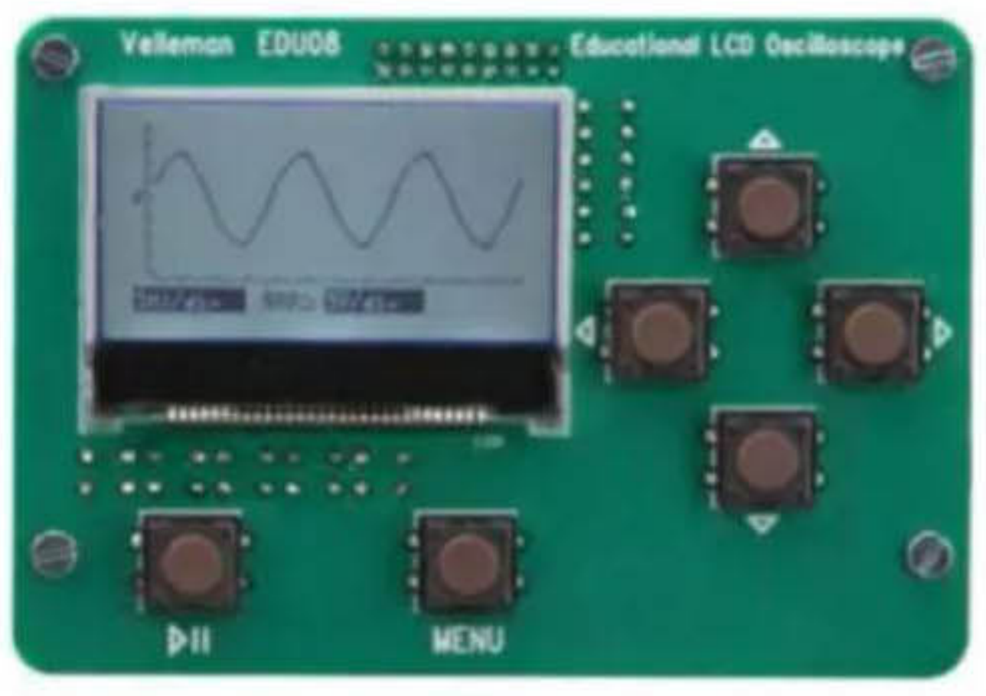

Build your own LCD oscilloscope with this exciting new kit. Learn how to read signals. See the electronic signals you learn about displayed on your own LCD oscilloscope. Despite the low cost, this oscilloscope kit has a lot of features found on expensive units like signal markers, frequency, dB, true RMS readouts and more. A powerful auto-setup function will get you going in a flash!
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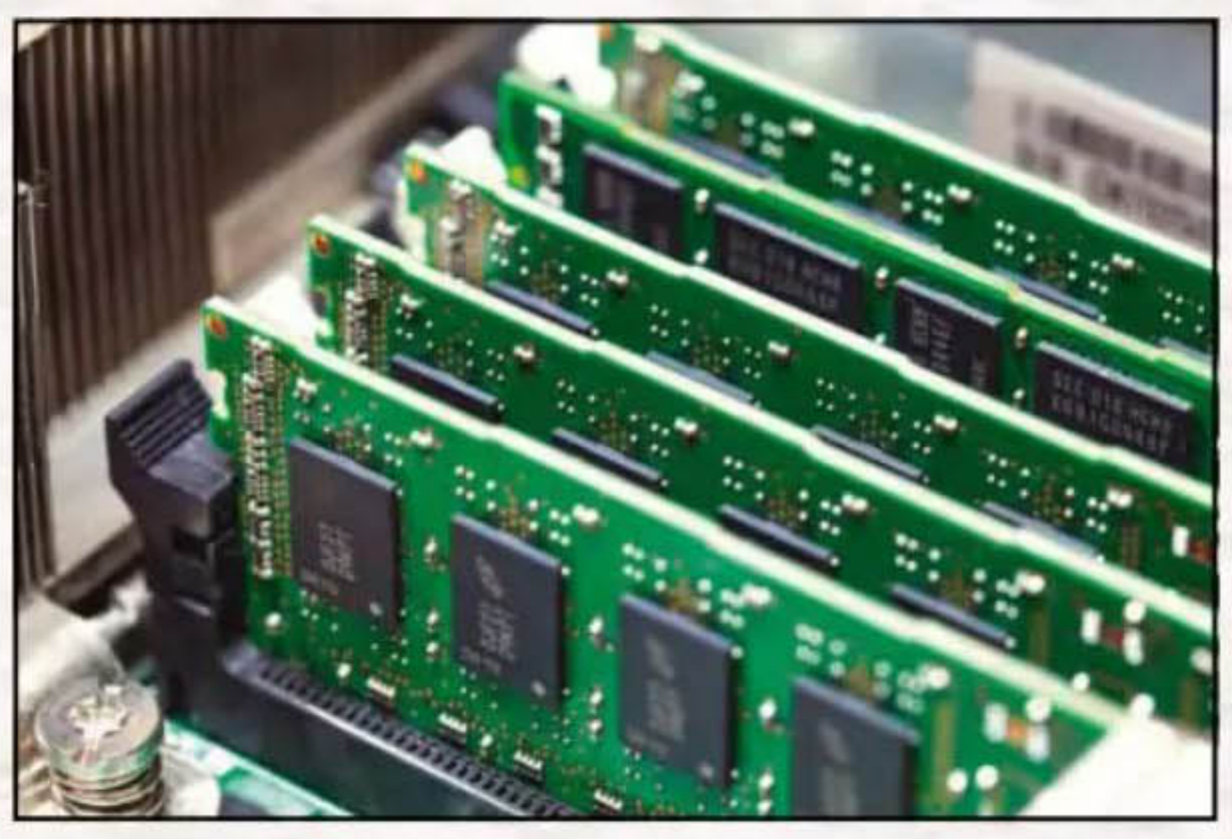

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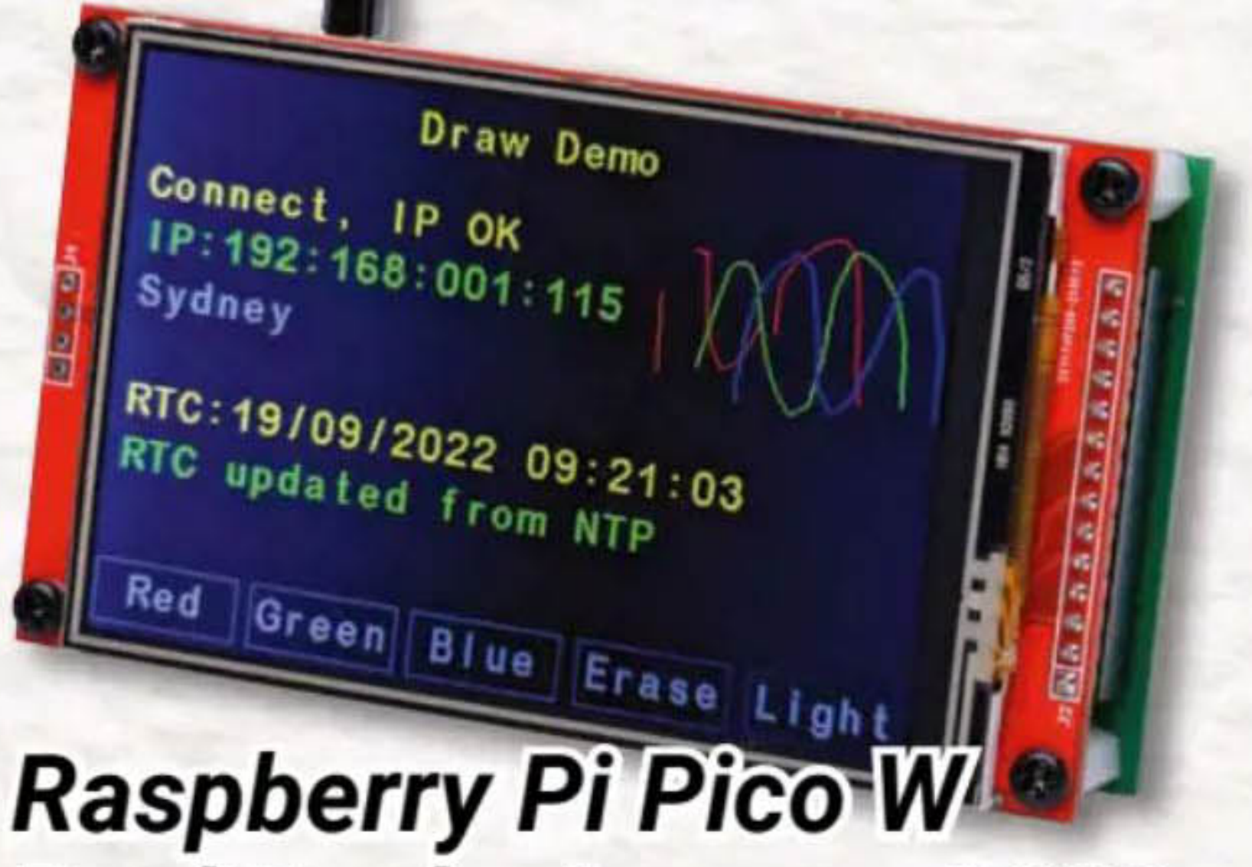
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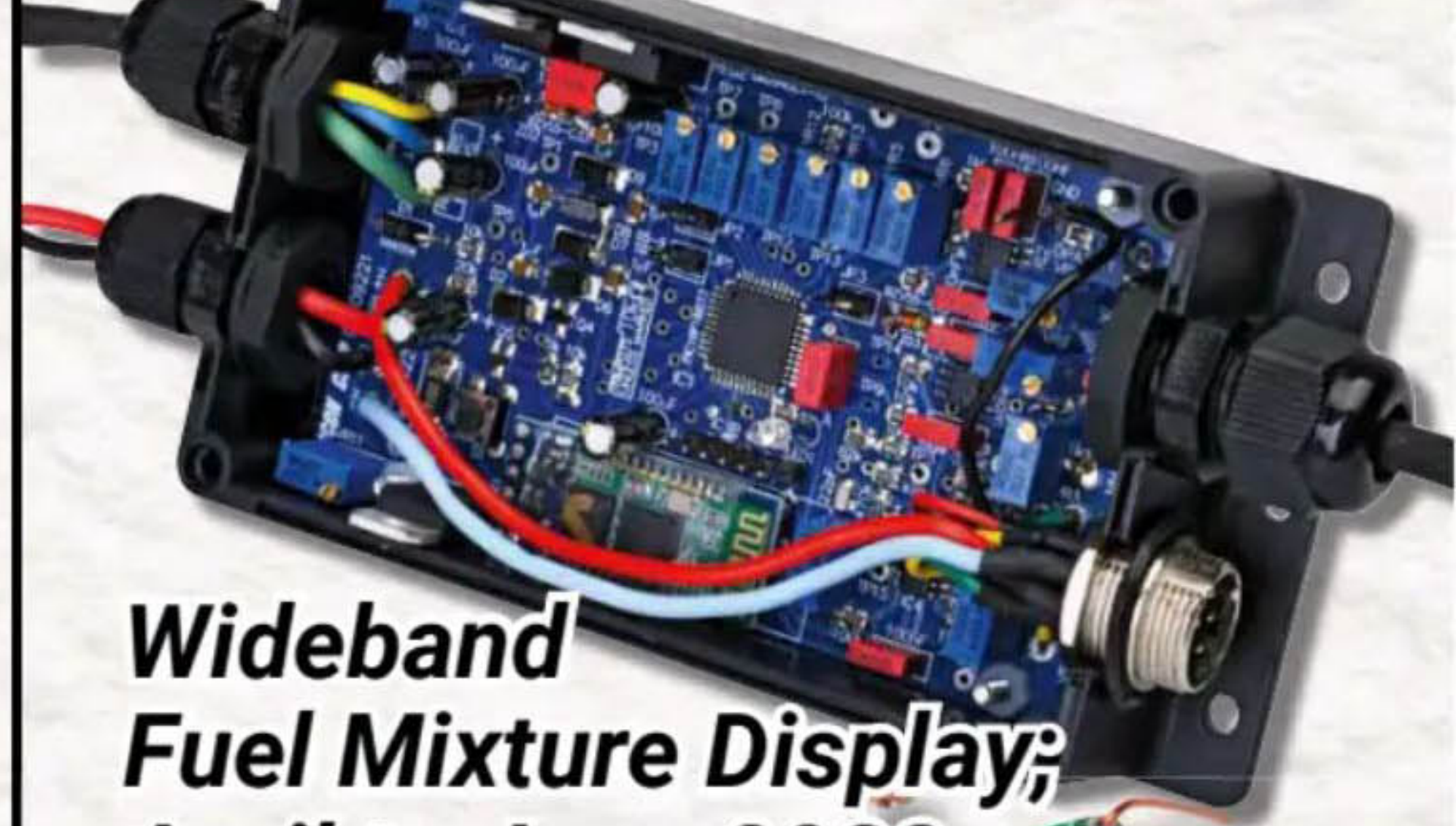
IP:192:168:001:115
Sydney
RTC:19/09/2022 09:21:03
RTC updated from NTP
Red
Green
Blue
Erase
Light

Raspberry Pi Pico W BackPack; January 2023



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We've come a long way

Hobby electronics has come a long way since the days when, nearly a century ago, constructors grappled with newly emerging vacuum tube technology to produce home-brew radio receivers of surprising sophistication and complexity. That was in an era when 'wireless' was one of the few practical hobbies available to budding 'makers'. (Woodworking was another.) Interest in radio intensified exponentially during the 1930s and magazine titles such as *Hobbies and Practical Wireless* appeared weekly to meet an insatiable demand for projects to challenge the hobbyist's practical skills.

Practical Wireless would become a standalone title aimed at the flourishing hobby radio sector while its sister magazine, *Practical Electronics*, followed in the early 1960s to exploit new semiconductor devices in a wider range of applications. The wannabe electronics constructor has been kept busy ever since!

Our hobby has of necessity mirrored global technological trends, and today's constructors embrace a wholly different set of skills compared with their forebears. Wikipedia reminds us that the first electric soldering iron dates back to 1889: appropriate for radio sets of yesteryear, perhaps, but some modern construction projects regularly use ready-made modules and tiny surface-mounted devices that are much smaller than a match head – a fact of life dictated to us by the electronics industry. Starting 25 years ago, boards full of discrete components were swept aside by the microcontroller, which demanded programming and coding know-how, aided by the use of software design tools. Thanks to our design partners at *Silicon Chip*, the class-leading projects found inside every issue take advantage of these modern components along with high-quality printed circuit boards that help ensure constructors can accomplish their latest project successfully. One thing that hasn't changed over the years, though, is the inspiration and variety that we at P*ractical Electronics* strive to bring our readers every month, offering constructors interesting and absorbing challenges to keep you just as busy as ever!

What will the future bring?

From circuits using glass vacuum tubes housed in wooden cabinets to the latest designs based on devices with a billion or more transistors in 3D-printed enclosures, electronics has changed beyond recognition. In fact, when it comes to electronics, change is the one constant you can rely on. So, what will the coming decades bring? AI, smarter sensors and faster devices seem certain, but I'm sure there will be surprises too. And that's all part of the fun!

Matt Pulzer
Publisher

Who saw that coming?

Techno Talk

Max the Magnificent

Cast your mind back to the year 2000. How many of the devices and technologies that surround us today did you see coming? Did you predict the advent of smartphones? Did you envisage tablet computers? Did you forecast the widespread deployment of AI?

We live in an age of wonders. Many of us don't appreciate just how lucky we are. For most of human existence, apart from the top 0.1%, people lived in abject squalor. They were cold, hungry, dirty, infested… and those were the lucky ones. Now our homes boast hot and cold running water, electric lights and heating (and cooling where I live). We issue spoken commands to artificial intelligences, our humongous high-resolution colour televisions show us what's happening around the world in real-time, and… I could go on and on.

Knowledge is power

There are two quotes that often spring into (what I laughingly refer to as) my mind. The first is the expression, *ipsa scientia potestas est* ('knowledge itself is power'), which occurs in Francis Bacon's *Meditationes Sacrae* (1597). And then there's, 'The simplest schoolboy is now familiar with facts for which Archimedes would have sacrificed his life,' which comes from Ernest Renan's *Souvenirs D'enfance et de Jeunesse* (1887).

I love to learn new things. I'm incredibly fortunate in that I get to chat with all sorts of people who know things with which to boggle my mind. Just the other day, for example, I was chatting with Dr Gerard Van Belle, who is Director of Science at the Lowell Observatory in Flagstaff, Arizona. He was telling me about all the telescopes and other technologies we now have at our disposal to vastly increase the sum of human knowledge about all sorts of things.

For example, we know that there's a star system that's located about 3,000 light years from Earth. Our name for this system is *T Coronae Borealis*, or *T CrB*. This system is to be found in that portion of the night sky we call the constellation *Coronae Borealis*. We know this is a binary system comprising a huge red giant and a white dwarf orbiting each other. We know the white dwarf is composed of electron-degenerate matter, which means that, while having the same mass as our sun (give or take), this mass occupies a volume comparable to the Earth (give or take).

We know the white dwarf is sucking hydrogen away from the red giant, resulting in it having a 'sea' of hydrogen a few meters deep. At some stage, the hydrogen will undergo a runaway thermonuclear reaction that will blow off the surface layer of the white dwarf. Known as a nova (as opposed to a supernova), we can predict (with a high degree of confidence) that this event occurred around 3,000 years ago, with the light reaching us sometime between the time of this writing and the end of September 2024, resulting in a magnitude +2 star that will be visible to the naked eye for a couple of weeks.

I don't know about you, but the fact we know any of this stuff blows my mind.

I can see you!

A few years ago, I started work on a hobby project I called my *Countdown Timer*. Its role in life was to count down the years, months, days, hours, minutes, and seconds to the commencement of my 100th birthday celebrations, which will kick off at 11:45 a.m. British Summer Time (BST) on 29 May 2057 (mark your calendar and stockpile the fireworks).

I put this on the back burner for a while (so many things to do, so little time to do them). Actually, I put it on a shelf in the closet. Unfortunately, the shelf collapsed, crushing all the display elements. 'Oh dear,' I said (or words to that effect).

I'm recreating this little beauty using vacuum fluorescent display (VFD) tubes – try to visualise a steampunk incarnation of 7-segment displays implemented using a mix of vacuum tube and cathode ray tube (CRT) technologies. The problem is that it's about 33 years (290,000 hours) to the great event, but VFDs have a life expectancy of only 10 years (87,000 hours). I'm going to feel rather silly if I don't know when it's time to start blowing my own (party) trumpet.

Fortunately, as I mentioned at the start of this column, we live in an age of wonders. For example, a company called Alif Semiconductor (**www.alifsemi.com**) recently announced a family of small, affordable, low-power microcontrollers (MCUs) capable of performing artificial intelligence (AI) tasks like voice processing and image recognition.

They also have something they call a Vision AppKit, which is a small circuit board the size of a large postage stamp carrying one of their processors and a camera. They are sending one of these bodacious beauties to me. It will be pre-programmed to recognise human faces looking toward the camera. I'm going to mount this on my *Countdown Timer*. When someone is looking toward the timer, the VFDs will shine in all their glory. If no one is looking, the timer will carry on counting but the displays will be powered down. Brilliant!

Who knew?

How good do you think you are with respect to predicting the future? We can base this on how good you were in the past. As we celebrated the year Y2K and the start of the current millennium, for example, did you predict the advent of smart phones that could take pictures and videos, act as MP3 players, and provide GPS functionality? Did you envisage tablet computers like the iPad? Did you forecast the widespread deployment of AI and the commercial availability of virtual reality (VR) and mixed-reality (MR) headsets?

Let's get a little closer to home – say a year ago. Were you expecting a little AI-enabled MCU like the one I described earlier to be available now?

Me neither. So, who *was* good at predicting the future?

Well, I recently read *A Story of the Days to Come* by HG Wells. Published in 1899, this tale is set in a dystopian future London of the 22nd century. People live in enclosed cities and travel around on moving walkways. Mega-corporations rule the world. The rich live in skyscrapers while the lower classes are relegated to subterranean dwellings. There are intelligent loudspeakers suspiciously the Amazon Alexa… Hmmm, maybe Wells' *Time Machine* was functional rather than fictional!

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The Fox Report

Barry Fox's technology column

Report from the Digital Television Group Summit

This year's DTG Summit – organised by the Digital Television Group, which standardises the tech needed to watch digital TV in the UK – coincided with news that the government and communications regulator Ofcom are looking at a timetable for switching TV viewing from traditional over-the-air linear broadcasts to Internet-based IP streaming delivery.

In October 2023, Ofcom launched a 'Call for Evidence' on how changing audience habits, in particular, the increase in Internet-based viewing, will affect the future of TV distribution. Over 75s are four times more likely to rely on digital broadcasting than Gen Z youngsters who have been brought up with streaming. Over 50% of 16-24 year-olds don't watch TV. They stream YouTube or Tik Tok, instead. Yih-Choung Teh, Ofcom's Director of Strategy and Research, compares the switch to IP streaming as 'comparable to Digital Switchover' when the UK very successfully ditched analogue TV.

'The tipping point will be when it is no longer viable for broadcasters to deliver digital television,' he says. This will come when not enough people are receiving broadcasts to justify the cost of transmitters.

But he assured that Ofcom is committed to 'not leaving people behind' and Minister for Digital Infrastructure Julia Lopez added the assurance that although 99% of TVs sold next year will be 'smart' and Internet-enabled, the government will not pull the plug on Digital Terrestrial Freeview until 2034. How this commitment will bind any future government and minister is unclear.

Careful how you change

Although no-one was blunt enough to mention it (or perhaps hadn't yet seen it with their own eyes) the Summit also coincided with a dramatic example of the perils of transitioning from broadcast to broadband delivery.

The struggling TV station TalkTV had just ceased normal broadcasting and switched to stream delivery. Anyone tuning an ordinary TV to TalkTV's Freeview channel 237 got a dark screen; anyone with a smart TV is – in theory – automatically redirected to Channel 294, which is a Freeview channel that automatically logs into an IP stream. In practice, and even with fibre broadband, the viewer waits what may be minutes to see a dark screen, then an invitation to press the remote control's Red Button (which appears unnecessary), then sees a message that connection may take 30 seconds and finally, after what may be minutes, gets to watch the programme. The delay probably depends on the quality of the smart TV.

I've also encountered problems with lost lip sync and stream freezing, with gaps so long that by the time the pictures and sound are up and running again, the topic being discussed has changed. And for some unexplained reason the news breaks contain no news.

It's a confusing mess and unless there are major advances, mixing IP and DTV effectively kills channel hopping.

Freely

The UK's public service broadcasters, BBC, ITV, Channel 4 and Five, are banking on a recently announced new service called Freely, which was being demonstrated in exhibition space at the DTG Summit.

Jonathan Thompson, Chief Executive of Everyone TV, the new company behind Freely, describes himself as 'a former director of strategy for Ofcom and Channel 4' with 'extensive experience of working in broadcasting and the regulatory environment'. He read a speech which said very little about how Freely works, just a lot about how Freely is 'a foundation for the future' which bundles 'everything from the public service broadcasters – Freeview terrestrial and Freesat satellite, along with the catchup services like iPlayer, in one place, for free'.

'All you need is Wi-Fi,' Thompson said (as long as the broadband speed is at least 10 Mbps). 'Freely provides multiple entry points. We continue to support Freeview and Freesat and Freeview Play. Freely just adds to the mix. We are at the start of a journey'.

Freely's demonstrators outside in the exhibition space were able to add a little more hard fact detail. So far, the only way to receive via Freely is to buy a new Hisense TV set with the Freely system built in. This takes in Freeview Digital Terrestrial broadcasts through a conventional aerial socket and broadband streams by Wi-Fi (and presumably also Ethernet). Freely numbers its channels differently from Freeview and Freesat. So Sky News is on channel 303 instead

The Home of Common Sense has moved to channel 294

Visit Talk.TV to find out more or listen via DAB+ and Smart Speaker

Press Red

Stream loading it may take up to 30 seconds to start

TalkTV has provided a masterclass in how not to transition from broadcast TV to IP streaming.

of 233 on Freeview, and 202 on Freesat; troublesome TalkTV is on Freely channel 305.

'It's a new platform with a new list that mixes DTT and IP that makes the Public Service Broadcasters more prominent' explains Freely.

Freely says it has struck a deal with Turkish company Vestel, to put Freely in its Toshiba, JVC and Bush TVs and is 'talking to LG and all the major TV brands'.

Narrow, expensive option

Seasoned broadcast engineers who regularly attend the DTG events were surprised at Freely's launch strategy – with the only available Freely product so far a costly TV set, and no consumer option to buy an add-on set top box or dongle that can be connected by HDMI cable to existing TVs, like an Amazon Fire Stick or Roku device.

'I don't change my TV every year' was how one broadcast engineer put it. 'It seems daft not to start with an add-on device'. A Freely spokesperson says Freely is 'talking' with all manufacturers and assures that there is no technical reason why a set-top box or dongle cannot be used to receive the new service. 'Cart before horse' is how one group of DTG delegates summed up Freely's launch strategy during the coffee break.

Facts, facts, facts

Regular readers will know that I work on the boring old principle that facts are king as a reference source, while conjecture, assumption and opinion are generally worthless. So, for the sake of completeness, I'll briefly put on record a couple of fresh hard facts relevant to the pieces I've written about self-protection when buying on line. Also, some fresh self-protection tips for the Internet Wild West.

Just for the heck of it and with zero expectations I filed a complaint with the Advertising Standards Authority about the convoluted way in which eBay promises protection under the Financial Ombudsman Services if things go wrong with eBay's Moneyback Guarantee scheme. In a memo nutshell, eBay in the UK comprises two quite different and separate entities: 1) eBay Marketplace, which is eBay (UK) Limited, accessed via the **eBay.co.uk** website and 2) eBay Commerce UK Limited.

eBay Commerce UK Limited (ECUK) provides payment services for sellers on the eBay platform and is regulated by the Financial Conduct Authority (FCA). The Financial Ombudsman Service (FOS) can investigate complaints for seller payment services.

The eBay Money Back Guarantee scheme managed by eBay (UK) Ltd covers purchases made via eBay's online market place eBay (UK) Ltd at **eBay.co.uk** and is not regulated by the FCA and not answerable to the FOS.

So the FOS cannot consider complaints about the eBay Money Back Guarantee because it is managed by unregulated eBay (UK) Ltd. The FOS can only consider complaints from sellers on eBay. I complained to the ASA that eBay has not been making this clear.

The ASA acknowledged my complaint with the now-standard convenient-for-the-ASA note that if a complainant hears nothing further from the ASA within 15 days, they should assume that the ASA is not investigating their complaint.

I duly heard nothing from the ASA so must assume that the ASA is not concerned about the eBay guarantee loophole. Perish the thought that it finds tricky legal issues, along with tricky technical issues, beyond its ken – however clearly presented.

Judge for yourself from the ASA's list of topics recently dealt with – there's not a single tech issue amongst them: **https://bit.ly/pe-mar21-asa1**

Perhaps what we need is new body, TATASA, The Tricky and Tech Advertising Standards Authority.

Going postal

Also, but with sub-zero expectations, I filed a test complaint about the way the impressively titled Postal Redress Service (POSTRS), run by the even more impressively titled CEDR (Centre for Effective Dispute Resolution), had handled my complaint about the way Royal Mail's impressive multi-tier internal complaints system had brushed aside diligently collated evidence showing delivery fraud inside Royal Mail. I complained that POSTRS/CEDR gave no reasons for complaint rejection.

POSTRS/CEDR excused itself thus, 'The CEDR Complaints Procedure does not allow any investigation to be carried out into a decision made by an adjudicator or the decision process adopted by that adjudicator or the evidence they choose to consider or give weight to.'

You have to hand it to them all. They are being paid good money to ensure no sane person would ever bother complaining about anything relating to Royal Mail.

More broadly it is now a sad fact of modern on-line life that most avenues of official complaint now lead to a brick wall of illusory concern for consumer well-being, with buck-passing middle managers hiding behind No-Reply email addresses. Just as the postmasters were repeatedly told what so many home computer users are so often told – 'you are the only person complaining'.

Fortunately, there are simple, effective ways to challenge amorphous big bodies that now routinely communicate from email addresses that bounce replies. The key is to go low-tech. The easy answer used to be to send the Chief Executive an entertainingly worded fax, addressed to the company's main fax number. The fax would then become an open letter for anyone in the office to read on its way to their boss.

Faxes are no more, but do not despair, there is still low-tech snail mail. Write an entertainingly worded letter to whoever is named as The Big Boss on the company's self-congratulatory website, and post it in an envelope personally addressed to The Big Boss. Companies don't now get many old-fashioned letters, so it's a safe bet yours will be read and enjoyed by many office staff before eventually ending up on the desk of someone senior. They will know it has already been widely read, so is not safe to ignore.

I've played this ruse three times recently, to an incompetent broadband provider, a hopeless press office at a national research lab and a devious university department head. In each case just one suitably worded snail mail letter to The Big Boss has triggered quite magical near-instant action from previously No-Reply employees.

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Net Work

Alan Winstanley

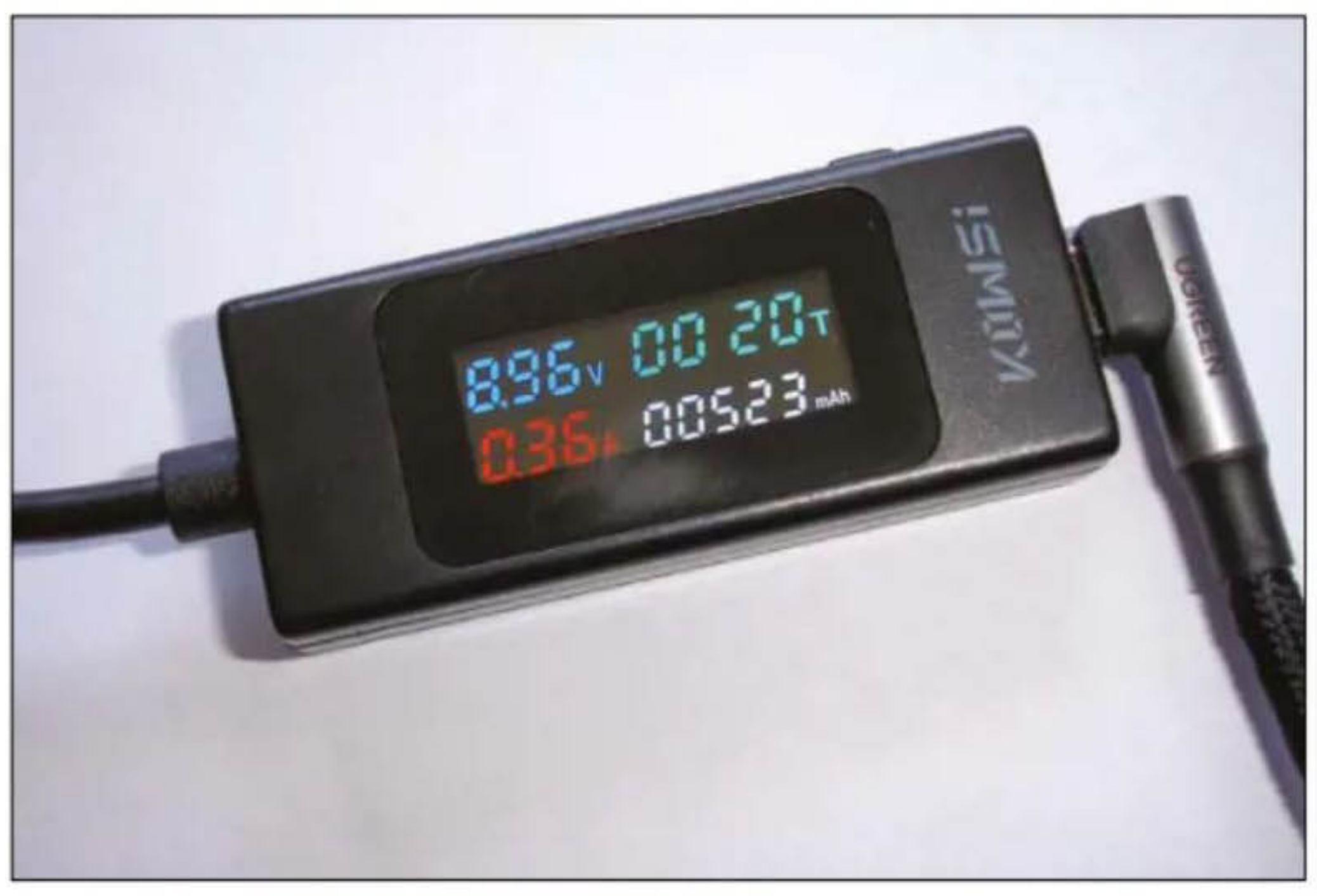
This month, more useful ideas for USB charging and monitoring are given, plus practical advice about hobby and craft adhesives found online, as used in precision smartphone repairs. There's more space programme news as well.

In last month's column I showcased some USB-powered products that typically use a 5V USB source to recharge their internal batteries. Whether it's a camping light, earbuds, Bluetooth speaker or a powerbank, it seems that almost every Chinese-made gadget or rechargeable device now arrives with a USB-C lead included for use with your own charger. Some USB leads might only cost a few pence to make and are often included just to add 'perceived value' to the product – I have a dozen scattered around, ready for the recycling bin. A 'hanked' lead is one formed by coiling it between two spindles or around a bar to produce a tidy coil, usually with a wire tie twisted round the middle or retained with a fancy sleeve. Apple addressed the thorny problem of producing hanked USB leads many years ago, by shaping them around two mandrels as shown in Apple's patent, downloadable from the US Patent Office at: **https://bit.ly/pe-jul24-pat**

Silicone cable ties and clips (pictured below) are available cheaply from Temu, and are quite handy for keeping USB leads manageable. (While I was at it, with online security in mind, I spotted some stick-on privacy covers for my laptop's webcam that work perfectly.)

The latest 'rounded-rectangle' USB-C connector is now commonplace and, as I showed last month, things get more interesting when 'Power Delivery' (PD) is involved: a PD-compatible source such as certain powerbanks and mains chargers can intelligently communicate with a device using a USB-C lead, raising the charging voltage to 9, 12, 15 or even 20V to deliver more power and cut charging times dramatically. Last month, I suggested some USB add-on monitors that show what's actually happening when USB-powered devices are being charged. Tiny digital meters are readily available that plug onto the end of a USB-C cable to display the power being delivered, and a 'PD' icon confirms when Power Delivery is operating. These gadgets are very handy for use with an existing USB charger cable.

Since last month, several more USB leads and monitors have arrived from China which I've been testing over the past few weeks. Basic monitors that use an A-type port such as the KOWSi USB Detector shown on p.11 last month display voltage and current, but I've now sourced a more versatile USB-C monitor that has an uncluttered multicolour display. The KOWSi KWS-065C is a useful thumb-size inline device showing voltage, current, wattage, capacity and elapsed time. It memorises readings until reset and the white segments can be cycled to show power, watt-hours and capacity. It supports the major charging protocols and is rated 4-30V at up to 6.5A. I like this general-purpose USB-C monitor – it's both clear to read and easy to use. The similar KOWSi KWS-066C crams more data on a colour display and shows temperature as well.



The KOWSi KWS-065C is a thumb-size inline USB-C monitor showing voltage, current, wattage, capacity and elapsed time, and is rated up to 6.5A.

Another KOWSi USB-C monitor, the KWS-2301C, has a 0.77-inch HD mono OLED readout that really impressed me: although more compact in size, its comprehensive display shows five lines of data including time, maximum values, CPU temperature and direction of flow.

It's rated up to 12A and the display is crystal clear, but having the eyesight of a sparrowhawk might help! KOWSi is a brand of Yuyao Lianke Electronics, and the products mentioned cost just a few pounds from AliExpress, though remember that AliExpress doesn't include sales tax in their on-screen prices.

Untangled cables

Higher-power USB charging cables are available that have a digital display built into a USB-C plug for convenience, and I managed to source a braided

(left) A 'hanked' computer lead is factory-made using a wire tie, but you can buy silicone straps or rubber clips from Temu to manage cables. (right) a stick-on privacy shutter for laptop webcams from AliExpress or Temu.

The KOWSi KWS-2301C offers a 0.77-inch OLED readout showing five lines of data, including direction of charging. It is rated up to 12A and will be very useful for monitoring high-power charging.

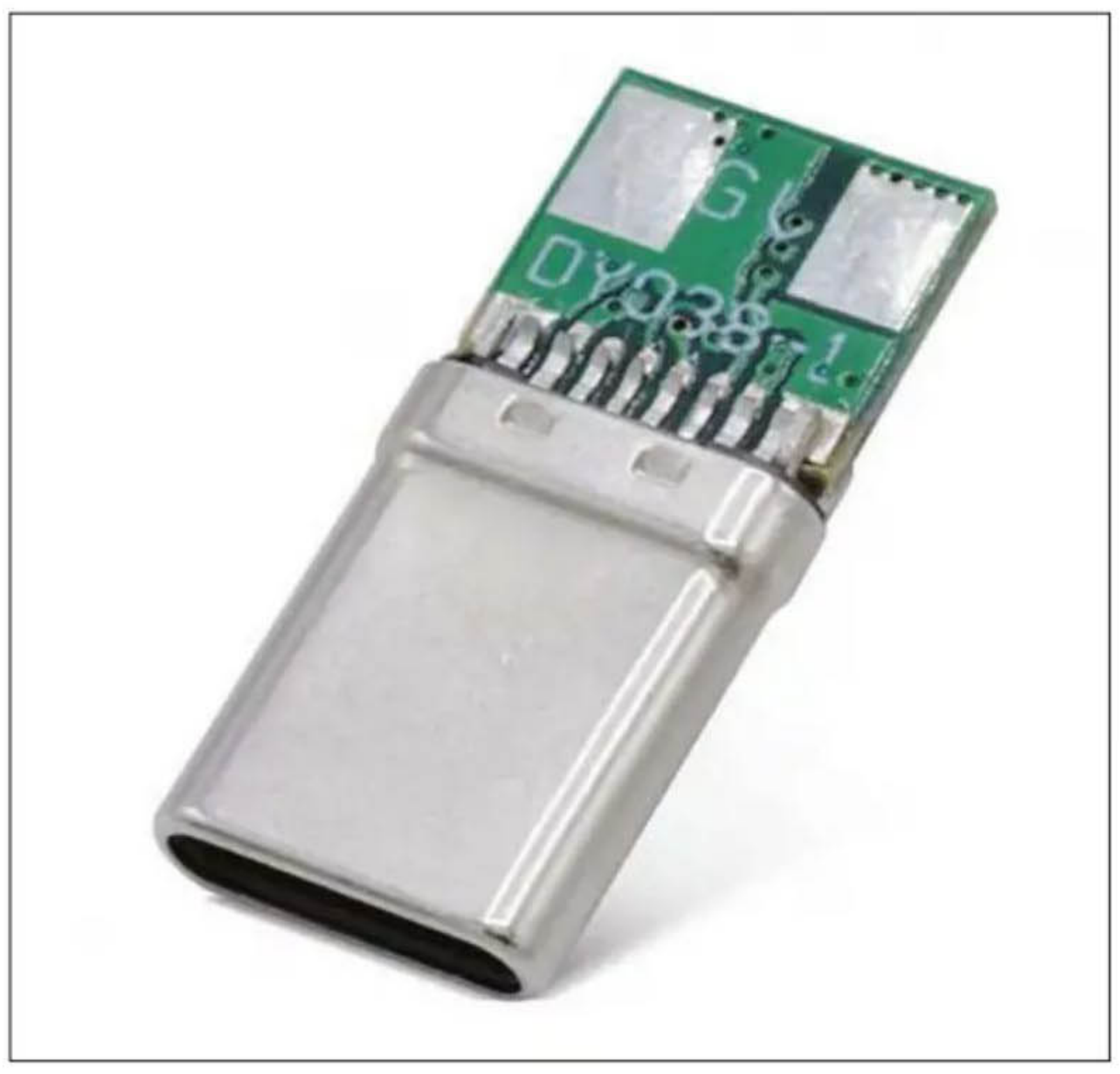
This braided USB-C lead by Essager has a built-in digital display for power and PD, and is tangle-free. It's rated at 100W, 7A.

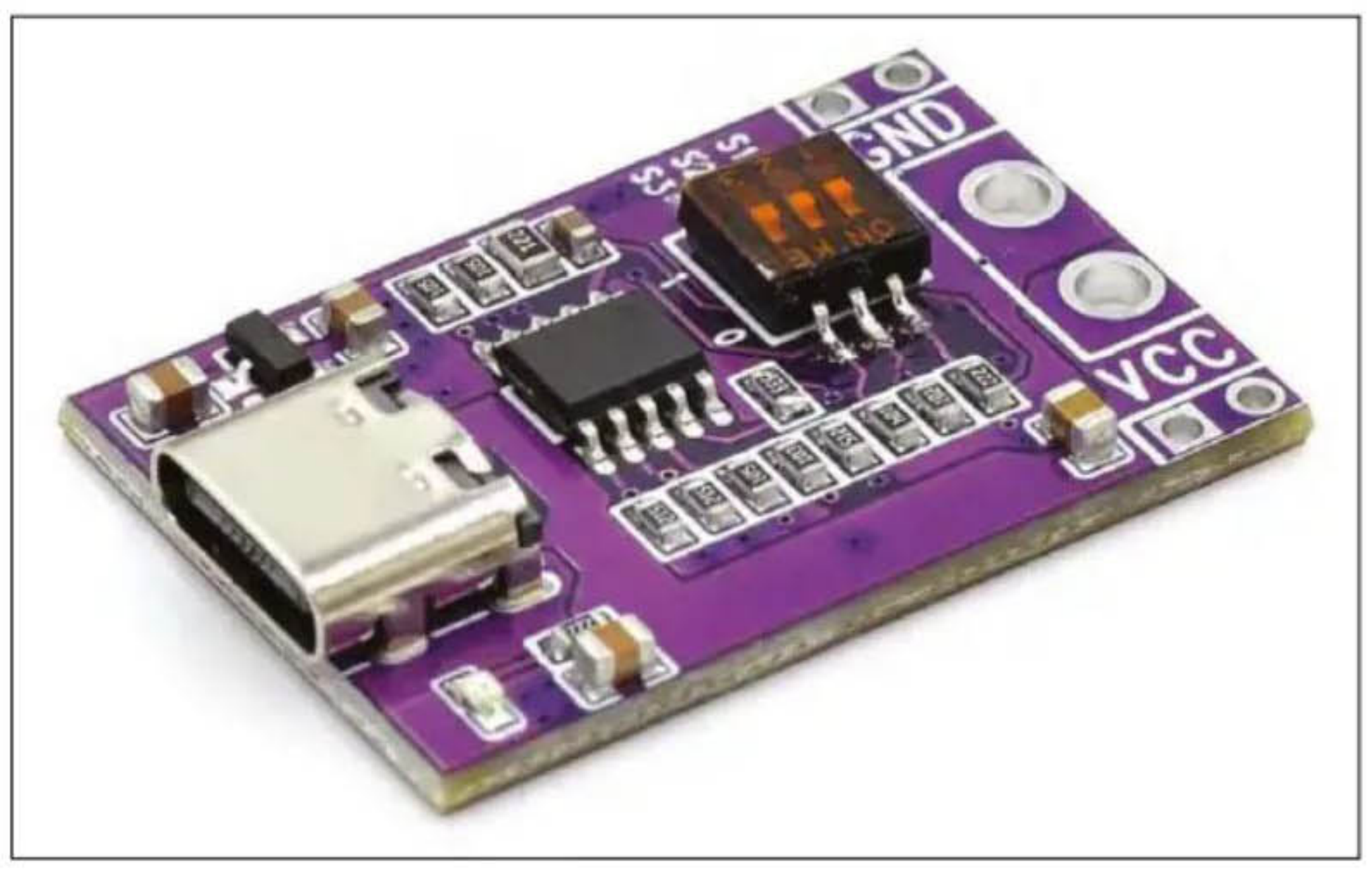
UGREEN offers quality braided charger cables of various lengths that are flexible and easy to manage. A right-angle braided USB lead offers a more compact connection that is less prone to accidental damage.

one-metre-long USB-C lead sold under the Essager brand. Just like the tiny inline USB-C monitors previously mentioned, it displays the wattage and PD (when available) on a small seven-segment display, which will be adequate enough for keeping an eye on a device's charging status. I liked the flexible and tangle-free braided sleeving, and the cable is rated by the makers at up to 100W, 7A. It would be handy when charging all sorts of small appliances that use a USB-C charger.

I also sampled some UGREEN brand braided cables that are 0.5m long, with A-type plugs at one end that will fit in my desktop USB charger. Again, the flexible 'memory free' cable sleeving helps to keep them tangle-free and twin packs are sold by Amazon. To help avoid accidentally causing damage to the charging port of, say, a smartphone or tablet, it might be worth considering using a right-angle USB lead which doesn't protrude so much. I found a short 0.5m braided type made by UGREEN on Amazon.

Powerbanks themselves are widely available and USB-C charging ports can be bidirectional: they are able to recharge the powerbank as well as charging a device. It's easy to overlook this, so it's worth double-checking the user manual to make sure. The KOWSi KWS-2301C mentioned earlier, clearly shows the direction of current flowing in a bidirectional connection.





(left) For experimenters, low-cost 'PD trigger' modules or 'decoy boards' can trick a PD power source to create a variable voltage DC supply for your projects. (right) A dip-switch type is also shown.

Electronics experimenters might be interested in some low-cost 'PD trigger' modules that are sold online. Also called 'decoy boards', they are designed to 'trick' a USB-C PD supply into outputting a higher voltage, for use as a DC power supply. Some use a dip switch to select the voltage while others work at a fixed voltage (9V through to 20V). User reviews are mixed, but the low cost makes it worth experimenting with them. AliExpress offer a variety of cheap ones and Amazon has one with dip switches, code B0BGPH1675 (illustrated below left).

Cracking under pressure

With high-speed charging currents now topping several amps, one wonders what effect that might have on the battery itself. More than ever, I don't leave devices on charge without supervision, nor leave them charging unattended overnight. My own smartphone has 'smart charge' monitoring that suspends charging to prevent abuse and extend battery lifespan, and the phone still works admirably after several years of heavy use. However, one of my nearly new powerbanks recently developed a worrying crack in the plastic case, an unwelcome sign of a swollen battery which was probably due to a

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This powerbank cracked after having some PD-level charging, which hints at a swollen and failing battery. It's not worth risking a fire or explosion, and will be discarded safely.

manufacturing defect or over-charging. It might be a co-incidence, but this defect only arose after I'd started using a high-power PD charger with it.

For the sake of writing off a few pounds, it's not worth risking a fire or potential explosion, especially when batteries are stored indoors, so it will be scrapped and disposed of safely in a proper recycling facility. It's highly dangerous to throw them away in general waste as they can rupture and cause a major fire, either in the garbage truck or back at the recycling site itself.

It seems that once their capacity reaches 20,000mAh, powerbanks can become heavy and unwieldy and certainly too inconvenient to carry, so I was attracted to a 10,000mAh sold by INIU (the same brand that sells a USB charging lead with built-in LED, see p.10 last month). This model BI-B61 is a PD 22.5W powerbank with a large digital display showing the remaining charge. It carries two USB A-type ports and a bidirectional USB-C port (5, 9 and 12V on PD) which are all clearly labelled. Its compact form factor is designed with portability in mind. Weighing in at just under 200g, a carry bag is included and there's a small pop-out phone stand as well. The INUI BI-B61 powerbank is guaranteed for three years and is available from Amazon (B08VD632WJ) along with higher capacity models.

Finally on this topic, with the forthcoming holiday season and air travel in mind, it's worth remembering that there are strict regulations regarding the carrying of lithium batteries, spare batteries and lithium-ion powered devices (which includes laptops, powerbanks, e-cigarettes and 'smart' luggage tags) on aircraft. The IATA rules regarding what should be 'carried on' and what cannot be stored in 'checked-in' baggage can be found on the IATA website, and a PDF is available at: **https://bit.ly/pe-jul24-iata1**

UGREEN
43%
22.5W
FAST CHARGE
DESIGN BY INIU

A 10,000mAh powerbank by INIU offers a digital display and PD. It is designed with portability in mind.

It will be worth double-checking with your airline before travel, and general dangerous goods guidance is published by IATA at: **https://bit.ly/pe-jul24-iata2**

Hello, can you speak up?

One of the joys of working with microelectronics is that it gives you confidence to handle tricky technical tasks such as smartphone or even quartz watch repairs. My Huwei smartphone suddenly went on the blink recently when I realised that callers could hear me, but I couldn't hear them, nor could I listen to any media soundtracks unless I used the phone's hands-free speaker. A built-in diagnostic program proved that the earpiece was faulty, so my first job was to search YouTube looking for ideas. Sure enough, a video showed that replacing the earpiece looked straightforward enough for a technical user, needing a few tools together with a particular adhesive to glue the phone back together again (more on that shortly).

Some 'pry tools' costing a pound or two were sourced from Temu. These flexible slivers of steel enabled me to carefully prise off the rear of my phone, but having quite sharp edges they need handling with care. The main challenge was probing around the case looking for a starting point, but after carefully gaining entry by a few millimetres the tools were used to slice through the glue seal around the perimeter of the case. The rear was then successfully removed, being careful not to damage the rear fingerprint sensor ribbon cable. (I ignored some incorrect guidance given in the YouTube video!)

Some spare earpieces had arrived from eBay costing just £5 for two, so after removing some tiny screws the new earpiece was carefully dropped into place with pointed tweezers. Many online sources alluded to a mystery adhesive dubbed 'B-7000', which piqued my interest because my former career had involved working for the country's largest contract filler of small containers, and at one time I witnessed the London factory in full swing, churning out thousands of tubes at a time (the superglue filling machine was especially temperamental).

Behind B-7000

I'd never heard of 'B-7000' until now, and a 15ml tube of this mystery glue duly arrived via eBay. It turned out to be a clear, self-levelling acrylic adhesive, dispensed via a needle-point nozzle

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THE OPENING TOOL
GB-5A
B-7000
GSE
Multi-purpose adhesives
0.5fl.oz(15mL)

Handy tools designed for prying open and disassembling electronic products are widely available online. A small tube of B-7000 adhesive is also shown.

with a low viscosity that allowed an accurate bead of glue to be drawn around the edge of the phone – you do need a steady hand. The phone rear could then be replaced and clamped together with some spring clamps while the adhesive cured. Excess glue is simply rubbed off, and after allowing some time for it to dry I'm happy to say my phone repair was successful, a satisfying result that cost me just a few pounds.

Inspecting the enigmatic tube of glue, I found it was an unbranded Chinese import with no hazard or handling data at all, nor even a manufacturer or MSDS (data sheet) was available, which rules out commercial or industrial use in Britain. I eventually found a likely-looking Chinese manufacturer called Zhanlida Adhesives who produce adhesives for DIY, craft, industry and hobby use. It's unclear if a similar-looking product found online, branded 'Bu Lai En', is connected with them: some dodgy English was apparent on the labelling.

Some readers might be interested in these glues and especially the ultra-fine dispensing needle tip designed for precise applications (though replacing the cap again is like threading the eye of a needle). I found B-7000 has the lowest viscosity in their range, which allows for accurate dispensing through a fine needle. I'm reminded of my chemical industry days, where lab technicians measured viscosity using a special apparatus (a viscometer) to test how 'thick' or resistant to a stirrer the fluid was. Viscosity is measured in milliPascal-seconds (mPas), or you may see the (obsolete) unit centipoise instead – every day's a school day! The makers state that B-7000 has a viscosity of 2800mPas. Other glues have different viscosities and hardness, and some are also offered in black (eg, T-7000). After trying the glue, I'll keep a tube or two of B-7000 in the workshop for delicate repairs. The product is on the usual websites and it will pay to shop around. A comparison of glue properties is published at: **https://bit.ly/pe-jul24-zhan**

Still on the subject of saving money with DIY repairs, I recently fitted a cherished Bulova quartz watch with a new battery, only to find that the watch stopped working altogether a few days later. Trying another battery made no difference, so it looked like a new Miyota movement (which are owned by Japan's Citizen Watch) would be needed. It's potentially do-able but needs a very steady hand and good eyesight, but then I found replacement circuit boards for certain quartz movements were sold online. I thought it was worth a gamble at £10 each and one arrived from Singapore. Sourcing some watch opening tools and a magnetic screwdriver, I successfully replaced the quartz controller circuitry, leaving the rest of the movement in situ. The screws measured just 0.3mm diameter, not much bigger than two full stops, and they will challenge any electronics constructor, but happily it all fitted back together perfectly and the watch sprang back into life. Faced with scrapping something or tackling a DIY repair, it's often worth browsing around the likes of AliExpress, YouTube and eBay as you never know what prizes and surprises you might turn up.

Readers interested in maintaining quartz watches, batteries and straps might find the author's *Watch Battery DIY Handbook* useful. It's A4 size and contains many worked examples and close-up colour photos of actual tasks, coin cell data and more, and is available on Amazon (B0CPBVG3K6).

Other news

China's space programme continues at pace. At the end of April, China's *Shenzhou-17* spaceship parachuted safely to Earth, bringing home three *taikonauts* after a six-month mission on board China's *Tiangong* ('Heavenly Palace') space station. There was also the successful launch in May of the 8.35 tonne *Chang'e 6* on board a *Long March* heavy lifter. This mission will follow the earlier *Chang'e 5* which landed in 2020, but it aims to land on the far (dark) side of the moon and, as a world first, bring

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A sample of Martian soil deposited into a small titanium tube by NASA's Perseverance rover, awaiting collection and return to Earth some time into the future.

two kilos of moon samples back to earth for analysis. Photos also showed that the lander carries a small, wheeled buggy, the purpose of which is unknown.

At the time of writing, we awaited news of Boeing's new crewed Starliner being launched by an Atlas rocket. The launch was postponed due to an oxygen relief valve problem. In *Net Work*, August 2023 I reported on NASA's grand plan for the Mars Sample Return (MSR) project, an extremely ambitious project to bring back to Earth soil samples that have been drilled by NASA's Perseverance Rover. Some two dozen samples from various locations have been collected (all methodically logged at: **https://bit.ly/pe-jul24-nasa**) and sealed in tubes ready for future collection. You can see the principle being tested at: **https://youtu.be/WLFyuRswVYA**

The MSR mission has now hit the Martian rocks, at least temporarily, having been deemed far too expensive at $10bn and also the 16-year timescale has been ruled excessive, so a re-design is now on the cards and less elaborate solutions are sought. For its part, Airbus UK in Britain had developed a new 'Sample Fetch' rover destined to land on Mars in 2028 and gather the sample tubes for transfer to a Mars Ascent Vehicle, ready to be returned to Earth. The £20m Sample Fetch rover was scrapped in 2022 but may be revived for future lunar missions instead.

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Chinese online vendor Temu continues to forge ahead and in the author's experiences so far, every order has been faultlessly delivered within seven days and the website is probably the slickest that he has ever used. It is sometimes hard to believe that it was not designed in Britain or America; a Chinese-language email received from Temu explains that their cross-border E-commerce platform is now second only to Amazon. In the UK, delivery is free but the minimum order is £15. You can sign up and 'shop like a billionaire' at: **www.temu.com**

Two years ago I brought news that a new 'gigafactory' for making EV batteries was being built by BritishVolt in north-east England to supply an emerging EV manufacturing industry (*Net Work*, May 2022). Sadly, the fledgling project collapsed into administration due to lack of funding. A year later the site was acquired by Australia's Recharge Industries, hoping to produce batteries for EVs and the military, but that proposal also hit financial problems and fell through. According to local press reports, the 235-acre former power station site, called Northumberland Energy Park 3, has been acquired by the US asset managers Blackstone and is destined to become a large-scale data centre, maybe operated by QTS Data Centers, to serve the needs of Google or Microsoft.

Google is building a 33-acre AI data centre in Waltham Cross, 12 miles north of London. Nearby residents complain bitterly about the construction work and loss of amenities. That's nothing: in North Lincolnshire, plans have been submitted to build a data centre five times larger, on a 185-acre greenfield arable site known as Humber Tech Park. The developers tease that it would be a hub for the AI industry and one of the largest in Europe. Construction plans include a 10m-high greenhouse that would utilise excess heat from the data centre, and possibly the local authority's swimming pool would benefit from heating being piped to it as well.

On the electric vehicle front, Storedot, proponents of 'XFC' extreme fast-charging EV battery technology, have demonstrated a Polestar 5 EV charging from 10% to 80% capacity within ten minutes. The demo consisted of a 77kWh battery pack with a consistent charge rate of over 310kW, peaking in excess of 370kW, with no overheating effects experienced throughout, they say. The technology aims to eliminate 'range anxiety' woes in EV owners.

Another acronym is destined to enter the EV lexicon in due course – the ASSB or All Solid-State Battery. Car maker Nissan explained its own ambitions for using solid electrolyte ASSBs, and the advantages over lithium-ion batteries, in an article that hints at the way that the EV industry is gradually moving: **https://bit.ly/pe-jul24-nissan**

Steep tariffs placed on Chinese EVs in America have kept them off the US market, so shiploads of them are apparently destined for Europe instead. Sources claim that more Chinese EVs cars are being produced than can possibly be sold, and new, unsold ones are stacking up and disrupting European ports. An interesting analysis is in a blog entry at: **https://bit.ly/pe-jul24-ev1**

As for the problem of scrapping old EVs, I'll close this month with a link to a Bloomberg news item which shows unwanted, obsolete EVs piling up and rotting away in China – you can see more at: **https://bit.ly/pe-jul24-ev2**

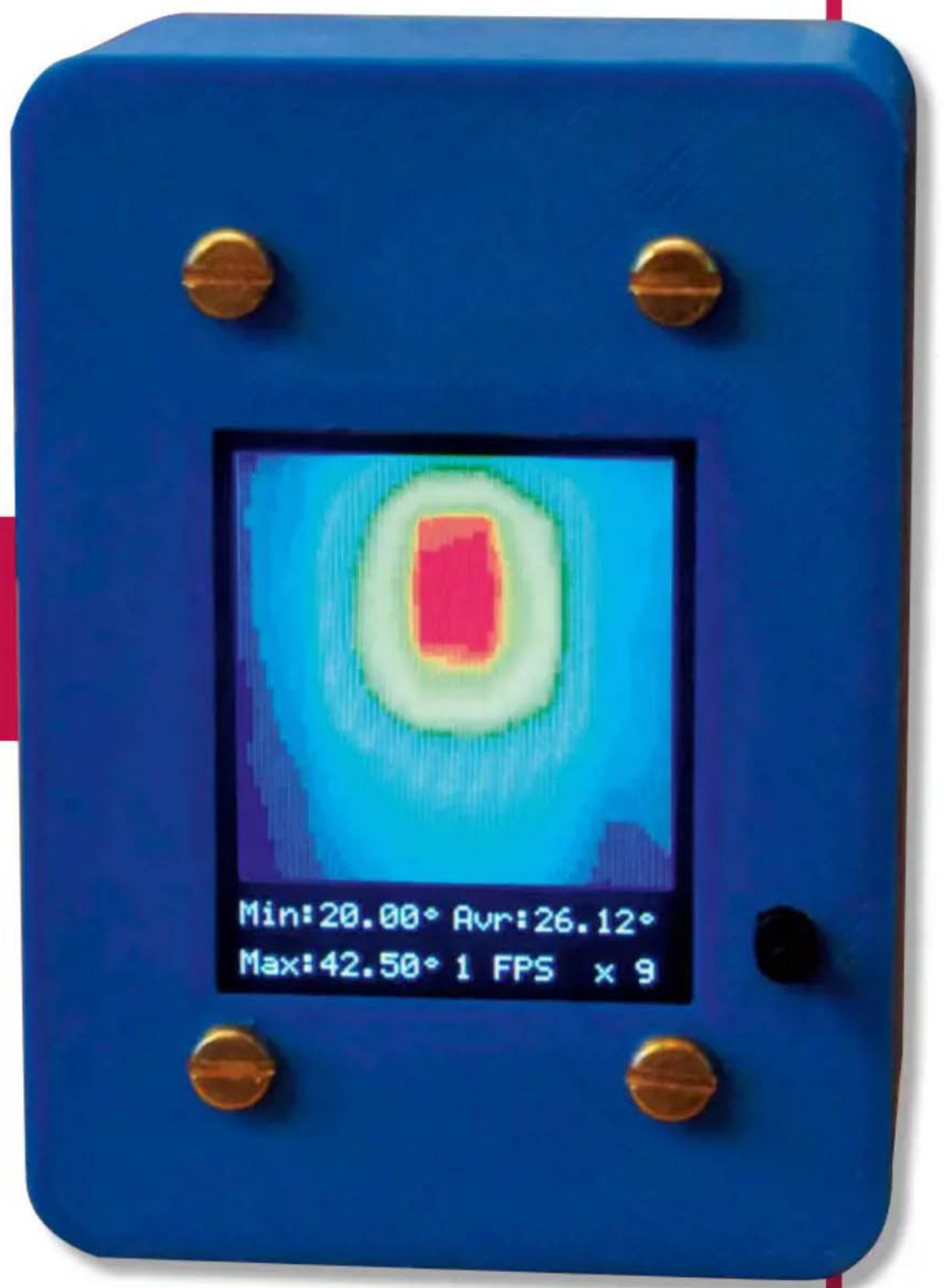
Don't forget the above web links are ready-made for you to click on in the *Net Work* blog at **electronpublishing.com**

See you next month for the latest from *Net Work!*

The author can be reached at:
alan@epemag.net

A thermal infrared camera measures hot or cold spots compared to the surrounding area. This is extremely useful in diagnosing hot spots in electronic circuits, which may indicate a failing component or the need for a heatsink. They can be pricey, but not this one, a DIY version that's easy to build.

Pi Pico-based Thermal Camera



by Kenneth Horton

IR thermal cameras have many uses beyond those listed above, such as checking for overheating mechanical bearings or identifying areas of heat loss in a building.

Panasonic produces the AMG8833 Infrared Array Sensor ('Grid-EYE') that detects IR emissions on a 64-pixel 8 × 8 array. It uses the I^2C serial protocol, so it can easily interface with a Raspberry Pi Pico running the PicoMite operating system.

Objects emit infrared energy in proportion to their temperature; the higher the temperature, the more IR energy is emitted and the higher its frequency. For really hot objects, the frequency extends into the visible wavelengths, which is why hot objects are seen to glow. By measuring this energy, we can get a pretty good idea of the temperature. However, there are some pitfalls, which we will mention later.

With the Grid-EYE sensor, each pixel has a viewing angle of approximately 7.5°, so the overall sensor has a viewing angle of 60° (7.5° × 8). Each pixel has a tolerance of ±2.5°C when operated within specification. We can minimise this error by calibrating the sensor, as described below.

Also, there can be random operating 'noise' of up to ±2.5°C per pixel. To reduce this, the sensor is used in moving-average mode, which averages two readings when the sensor is set up for a 10Hz frame rate or 20 readings when for a 1Hz frame rate.

If the raw output of the Array Sensor is displayed directly on an LCD screen, it appears very 'blocky'. Still, it can easily be upscaled using a technique called bilinear interpolation to give the appearance of many more data points. The PicoMite Thermal Camera can upscale by factors of two, four or nine. These factors were chosen as they make the best use of the screen width.

Below the thermal image display is a text read-out showing the maximum, minimum and average temperatures and the current operating mode.

As mentioned above, the Array Sensor can sample at 10 FPS (frames per second) or 1 FPS. The former is most suited to fast-changing subjects, while the latter better smooths out random noise in the sensor, giving a more stable and accurate output.

Bilinear interpolation

This involves drawing an imaginary straight line between two data points, then generating new data points in between that lie on that line. It's a simple technique that produces a much smoother-looking result than the more basic 'nearest neighbour' technique that gives a blocky image.

More complicated interpolation schemes like trilinear, bicubic, Lanczos or anisotropic interpolation involve considerably more processing (arithmetic) than bilinear. In this case, their advantages are minor; bilinear gets us most of the improvement compared to no filtering with very little processing.

Object emissivity

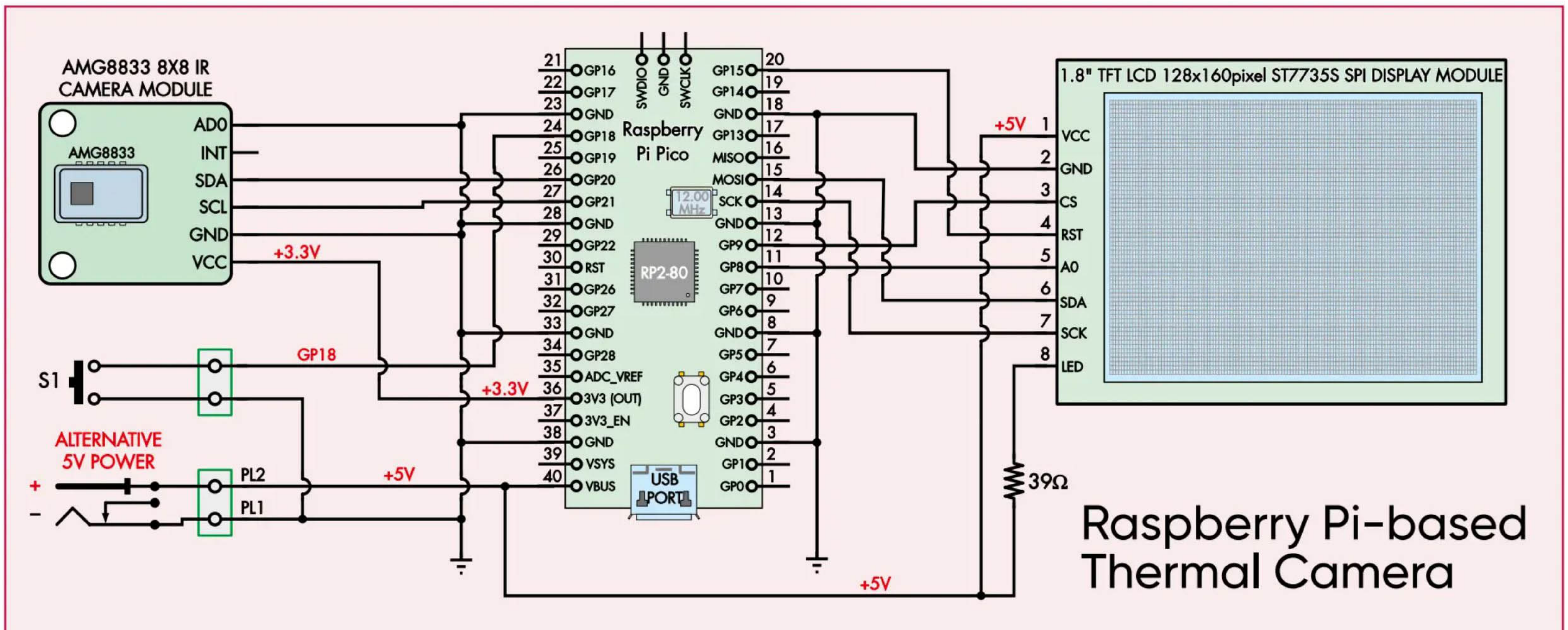
The 'fly in the ointment' for a thermal camera is that objects vary in emissivity. An ideal IR emitter is called a 'black body' with 100% electromagnetic emission/absorption.

Shiny objects like mirrors have an emissivity closer to 0%. If you point an IR thermometer or camera at them, you will measure the temperature of an object that the mirror is reflecting, not the mirror itself.

Luckily for us, many electronic components are dark colours and will have an emissivity of at least 90%, so a thermal camera will measure their temperature accurately. Human skin has an emissivity of 97-99.9%, so IR thermometers also work well for measuring our temperature.

This isn't a fatal flaw but be aware that the temperature measurements of metallic objects using this IR camera could be inaccurate. It isn't just well-polished metal surfaces either; even rough, oxidised aluminium only has an emissivity of about 20%, with polished metal surfaces usually below 5%.

A known work-around to measuring the temperature of shiny surfaces (eg stainless steel pipes) is to apply some matte painters tape, which has


AMG8833 8X8 IR CAMERA MODULE
AMG8833
AD0
INT
SDA
SCL
GND
VCC
+3.3V
GP18
S1
ALTERNATIVE 5V POWER
+
–
PL2
PL1
+5V
+3.3V
Raspberry Pi Pico
SWDIO
GND
SWCLK
21 GP16
22 GP17
23 GND
24 GP18
25 GP19
26 GP20
27 GP21
28 GND
29 GP22
30 RST
31 GP26
32 GP27
33 GND
34 GP28
35 ADC_VREF
36 3V3 (OUT)
37 3V3_EN
38 GND
39 VSYS
40 VBUS
20 GP15
19 GP14
18 GND
17 GP13
16 MISO
15 MOSI
14 SCK
13 GND
12 GP9
11 GP8
10 GP7
9 GP6
8 GND
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2 GP1
1 GP0
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2 GND
3 CS
4 RST
5 A0
6 SDA
7 SCK
8 LED
39Ω
+5V
Raspberry Pi-based Thermal Camera

Fig.1: the Thermal Camera circuit is straightforward, with the IR sensor array (MOD1) communicating with the Raspberry Pi Pico over an I^{2}C bus (SDA/SCL) and the LCD screen being driven over an SPI bus (CS, SCK and MOSI). The only other components are the pushbutton for changing modes (S1) and a 39Ω resistor to set the LCD backlight current.

a better emissivity. For more information, see: **https://w.wiki/6R6E**

Circuit details

Refer now to Fig.1, which shows that the hardware for the project is relatively straightforward. It consists of just three modules: the Infrared Array Sensor, a Raspberry Pi Pico running the PicoMite operating system (MMBasic) and a 1.8-inch SPI TFT LCD screen with a display resolution of 128 × 160 pixels and an ST7735 controller.

The sensor array is connected to the Pico via an I^{2}C interface, while communications with the LCD screen are over an SPI interface. The only passive components are a pushbutton to change modes and a 39Ω resistor to set the current at which the display backlight operates. The following Pico GPIO pins are used:

GP08	LCD data/control (D/C)
GP09	LCD chip select (CS)
GP10	LCD SPI clock (SCK)
GP11	LCD SPI data (MOSI)
GP15	LCD reset (RST)
GP18	pushbutton sensing
GP20	AMG8833 I^{2}C data (SDA)
GP21	AMG8833 I^{2}C clock (SCL)

The double-sided PCB is a carrier for the three modules, the pushbutton and the resistor. The display runs from a 5V DC supply from the Pico. On the Pico board, this is stepped down by a regulator to 3.3V. That 3.3V runs the RP2040 microcontroller on the Pico and is also available off-board, where it is used to power the AMG8833 IR sensor array.

The array sensor is available from the usual auction sites pre-mounted on a breakout board, and you can find the display on the same sites. There are some suggested links in the parts list.

The prototype was powered via the USB port on the Pi Pico, but there are also pads on the PCB for an external 5V power supply. This way, the Thermal Camera can be powered by a battery.

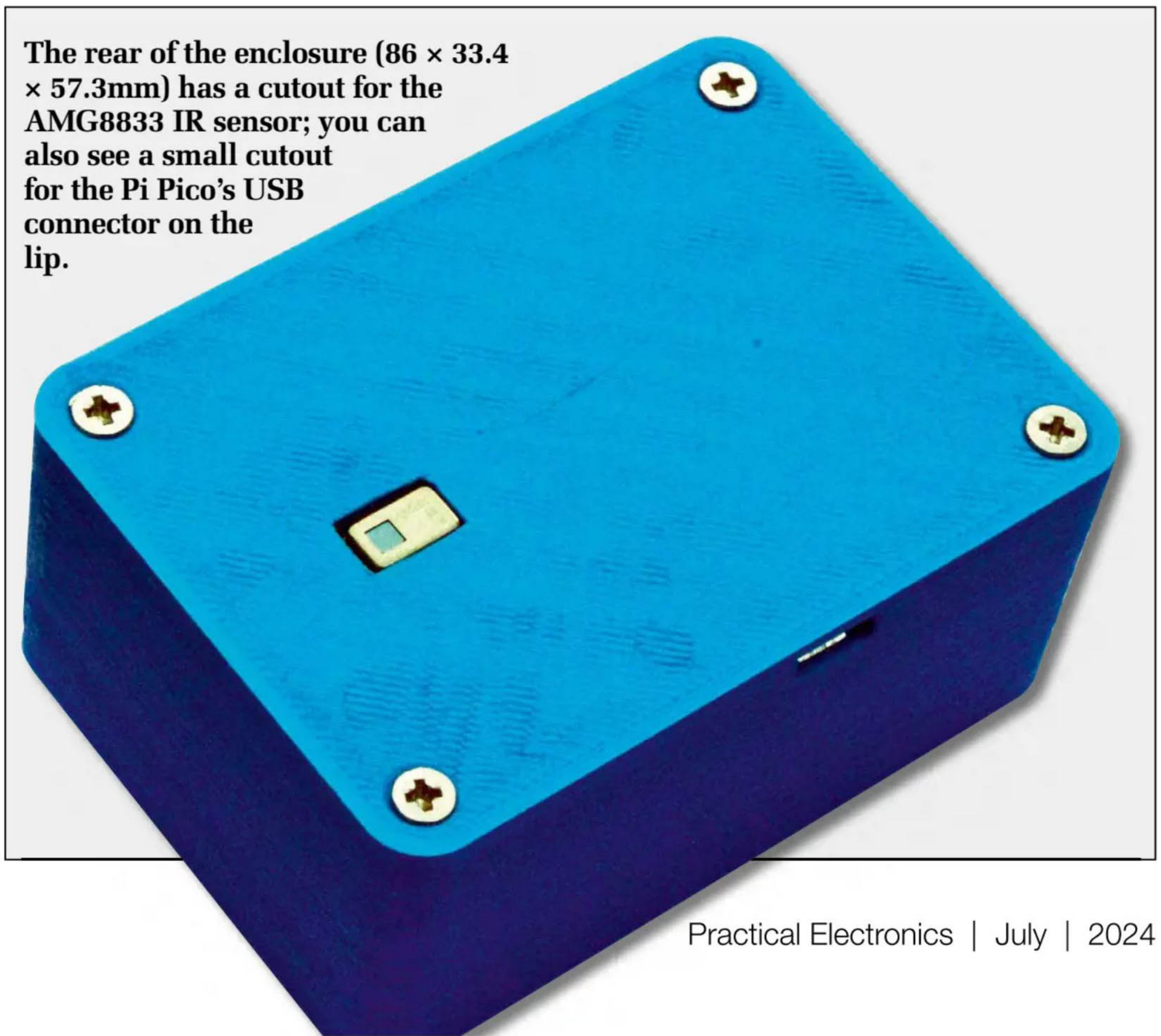
The pushbutton is connected so that it pulls the GP18 pin to GND when it is pressed. The Pico has an internal pull-up current enabled on that pin, so its voltage is high when the button is not pressed and goes low when it's pressed, allowing the digital input to sense the change.

Software operation

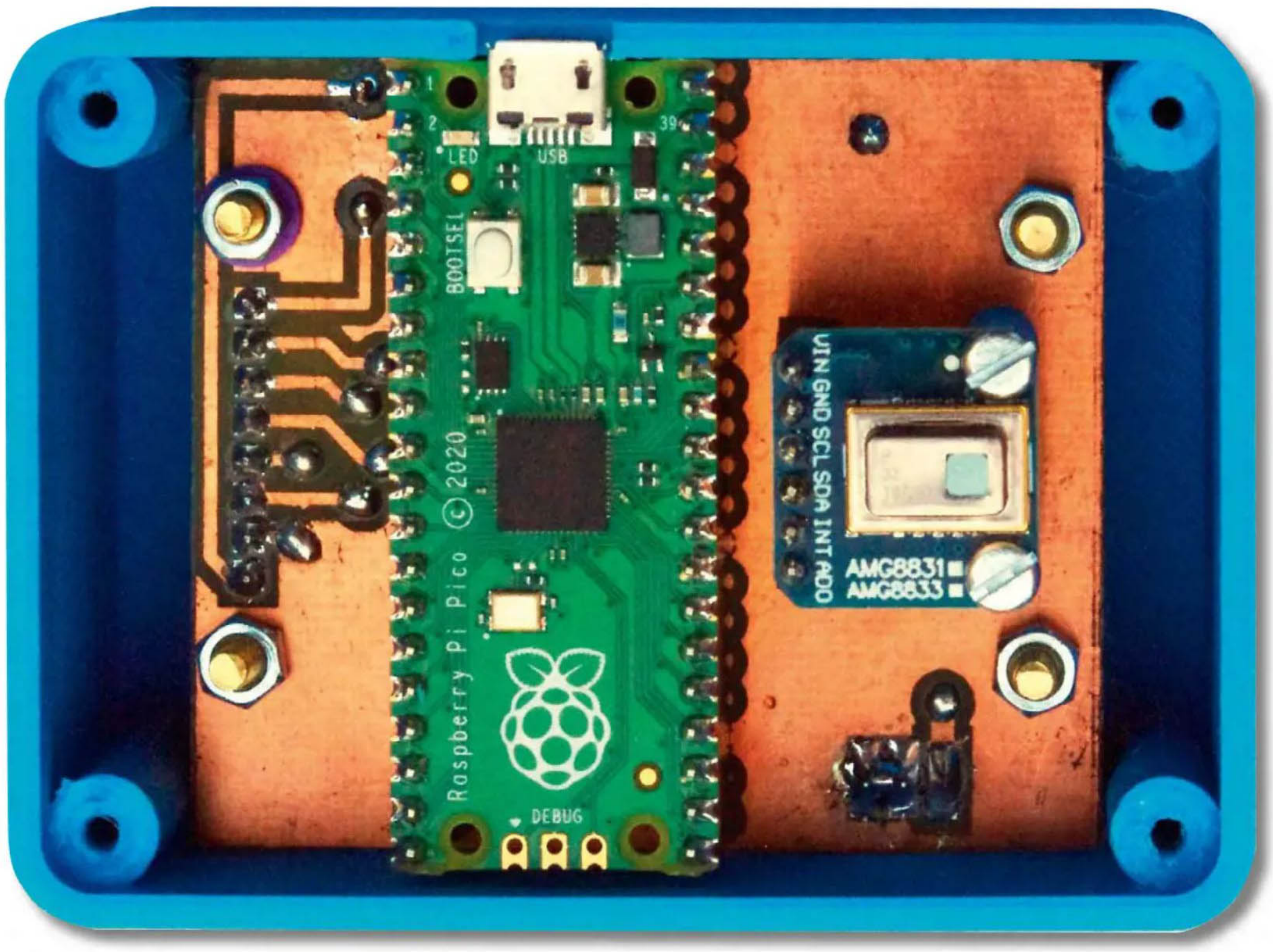
The basic flow of the program is:

1. Initialise the PicoMite, LCD screen and IR sensor array
2. Restore the calibration data and last pushbutton settings
3. Load the colour spectrum from the table
4. Enter the main loop
   - **a.** Read 64 pixels from the sensor and adjust with the calibration data
   - **b.** Calculate the maximum, minimum and average temperatures
   - **c.** Convert the absolute temperatures to points on the colour spectrum
   - **d.** Interpolate the intermediate colour values for each row using bilinear interpolation
   - **e.** Interpolate the intermediate colour values for each column using bilinear interpolation
   - **f.** Update the display
   - **g.** Check the pushbutton state
   - **h.** Delay if necessary

Repeat items a-h above indefinitely



The rear of the enclosure (86 × 33.4 × 57.3mm) has a cutout for the AMG8833 IR sensor; you can also see a small cutout for the Pi Pico's USB connector on the lip.



The Raspberry Pi is mounted on pin headers in sockets to make it easy to replace.

LCD screen limitations

Although the LCD screen is, in theory, a standard item, displays from different suppliers have different characteristics. One display tested had the red and blue colours reversed, while another batch had random pixels at the bottom and right-hand side of the display. As a result, three constants are defined to allow the program to be tailored to the attached display:

```
' Set to false for RGB displays
  and true for BGR displays
Const BGR_display = False
' Some ST7735 displays have a
  pixel alignment problem! Try
  = 2
Const HRES_offset = 0
' Some ST7735 displays have a
  pixel alignment problem! Try
  = 1
Const VRES_offset = 0
```

Despite the display supposedly having 65,536 colours, they can't actually show that many. First, RGB(247,251,247) is one step down from white but looks significantly dimmer. The difference between this and the next step down, RGB(239,247,239), is less noticeable, as is each subsequent step.

For dimmer values, the less effect each step has. RGB(127,127,127) is very dim, and RGB(63,63,63) is almost black! Another, more technical way of saying this is that the display has a very high gamma value.

As a result, it is difficult to get more than about 38 distinct colours across the spectrum (even with a good imagination), and the span from yellow through green to cyan seems particularly compressed! Also, the display is extremely sensitive to the viewing angle and must be viewed head-on to get the full spectrum of colours. Otherwise, adjacent colours blend into each other.

Construction

The Thermal Camera is built on a double-sided PCB coded 04105231, measuring 60 × 52.5mm and available from the *PE PCB Service*. The components are mounted as shown in Fig.2 and Fig.3.

There are nine vias on this board. If you are using a commercially-produced board (such as the one sold by *Practical Electeonics*), they will be plated, and nothing else needs to be done. If you etch the board yourself, those nine vias need to be drilled and short wire links soldered between the top and bottom layers in each location.

The LCD screen and switch mount on the underside of the PCB, while the Pi Pico and IR sensor are mounted on the top.

For convenience, the three modules can be mounted via socket strips rather than soldering them directly to the PCB. You can cut the sockets from longer strips if you don't have 6-pin and 8-pin sockets. The resistor can be mounted on either side of the board.

The switch is a two-pin or three-pin SIL-type vertical pushbutton that solders directly to the PCB. Alternatively, there is a provision in the 3D-printed enclosure to mount other types of pushbutton below the LCD screen and wire them up to the pads on the board using short connecting wires.

Once plugged into its socket, the IR sensor is secured to the board by two 20mm-long M2.5 machine screws and nuts with 3D-printed spacers (Fig.4) between the PCB and sensor. One of the spacers for the IR sensor has a cut-out to fit around an SMD component next to the module's mounting hole.

With the IR sensor array and LCD attached to the PCB, now is also a good time to plug the Raspberry Pi Pico into its sockets.

You can print the custom-made enclosure in two parts (body and lid), shown in Fig.5. The STL 3D printer files are optimised for 0.2mm layer height, 0.4mm wall thickness and 100% fill; they can be downloaded from the July 2024 page of the *PE* website: **https://bit.ly/pe-downloads**

Note that the first layer of the screw holes is filled as it gives a more pleasing appearance to the front and back of the case – just drill them out after printing. The holes in the lid are countersunk under the top layer and are best cleared with an 8-10mm drill by hand.

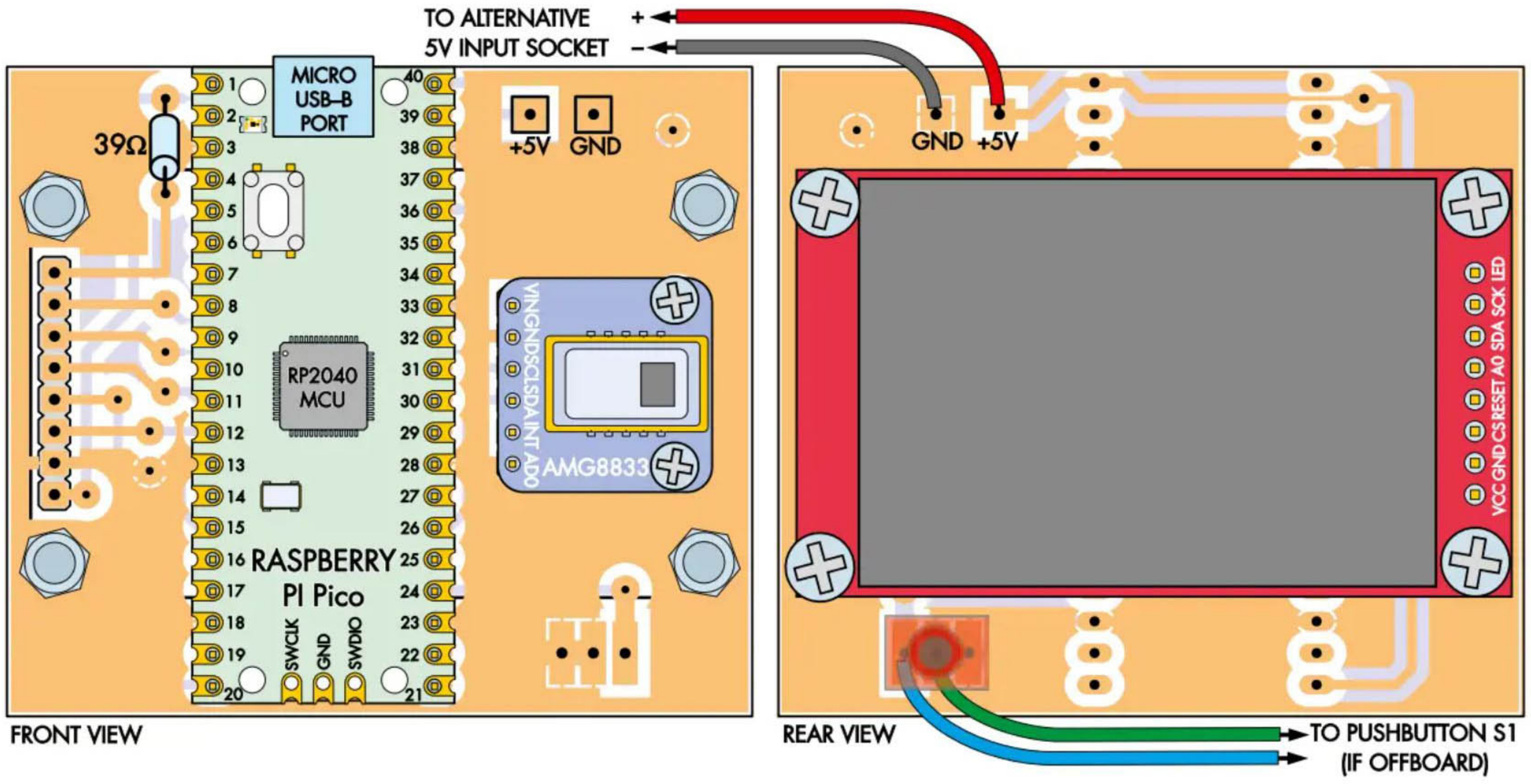
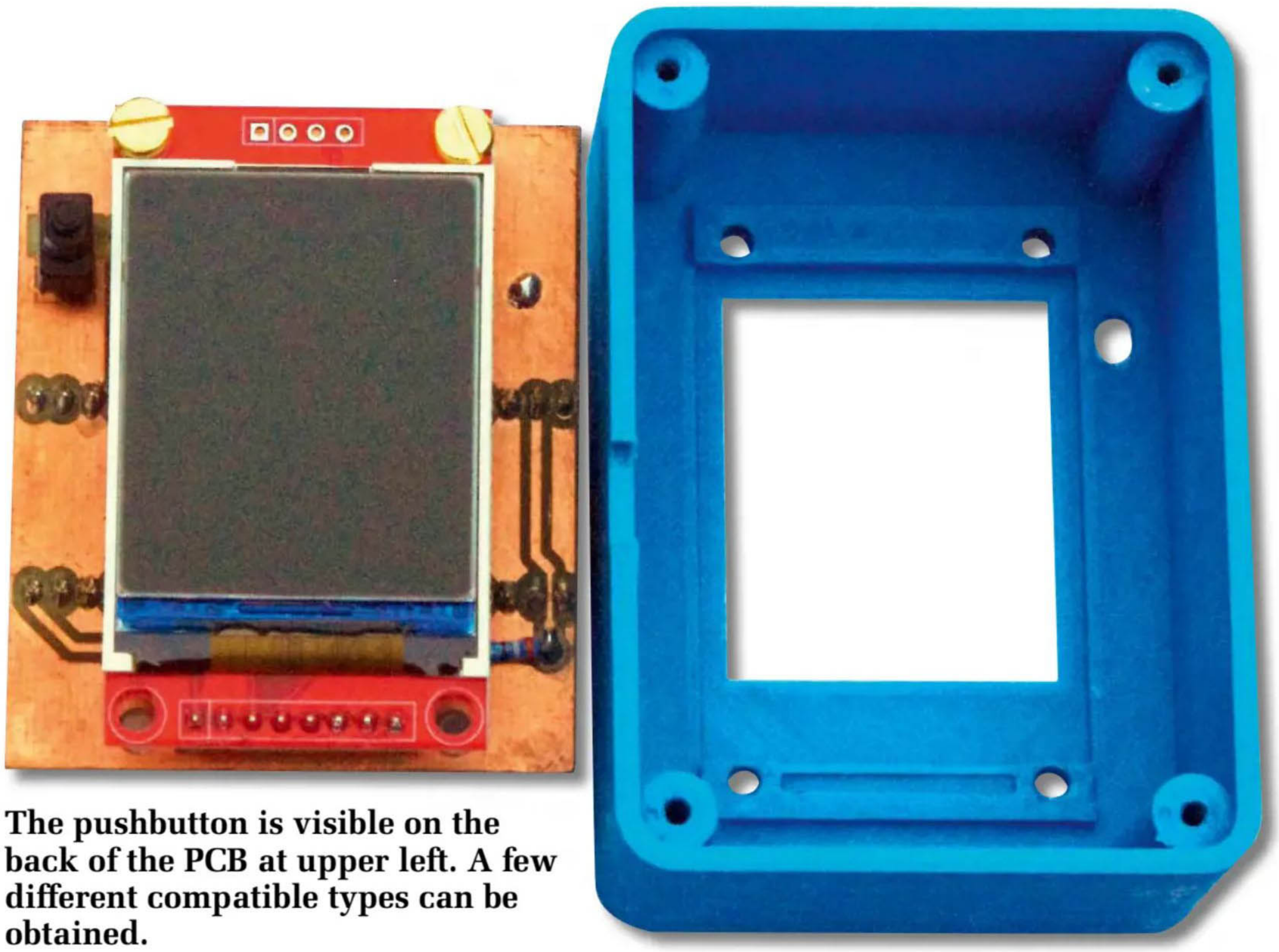


Fig.2 and Fig.3: components are mounted on both sides of the board. On one side are the Raspberry Pi Pico and IR sensor, both plugged in via header strips. The LCD screen, pushbutton and resistor are mounted on the other side, although the resistor can go on either side.

The PCB assembly is held in the case by four 25mm-long M3 machine screws and nuts, with 3D-printed spacers between the display and the PCB at the opposite end to the connector. It is necessary to insert the display into the case first, insert the machine screws from the front of the case, place the spacers over the screw shafts and then plug the PCB onto the display. Finally, secure it with the nuts.



The pushbutton is visible on the back of the PCB at upper left. A few different compatible types can be obtained.

Loading the software

Many readers will be familiar with loading PicoMite software, which was described in the article on the PicoMite in the July 2022 issue (*Make it with Micromite – Part 37*); briefly, an overview is:

- Download the PicoMite operating system and unzip the file from: **http://geoffg.net/picomite.html**
- To load the operating system onto the PI Pico, plug the USB cable into a PC while holding down the white button.
- The Pi Pico will appear as a USB drive. To that drive, copy/drag the file **PicoMitexx.xx.xx.uf2**
- Connect to the PicoMite's USB serial port using your preferred serial terminal emulator (eg, TeraTerm or PuTTY).
- Once connected, enter each of these commands in turn, but note that many of them reset the Pi Pico, so the USB connection is lost and will need to be restored before entering the next:

```
OPTION RESET
OPTION CPUSPEED 252000
OPTION SYSTEM SPI
  GP10,GP11,GP12
OPTION LCDPANEL
  ST7735,RP,GP8,GP15,GP9
OPTION SYSTEM I2C GP20,GP21
```

- The following two commands are optional; the first shows you what you have configured, while the second lets you verify that the LCD screen is working:

```
OPTION LIST
GUI TEST LCDPANEL
```

- Finally, load **Thermal camera.bas** into the PicoMite, again using your preferred serial terminal emulator or MMEdit. Use the 'Autosave' or 'XMODEM receive' commands, depending upon your preference.
- If you'd prefer to skip most of the above sequence, you can download the **Thermal camera (RGB).uf2** or **Thermal camera (BGR).uf2** file from the *PE* website and upload it in the third step above. That's equivalent to running all the configuration commands and loading the BASIC code. The only difference between the two files is the expected LCD screen configuration, so if the displayed colours are wrong, load the other file.

Operation

The pushbutton has the following functions:

- Short press (less than 1.5 seconds): cycles the display scaling factor through 1, 2, 4 and 9
- Long press (more than 1.5 seconds): toggles between 1 FPS and 10 FPS
- Very long press (more than 10 seconds): enters calibration mode

Note that the frame rates are sensor refresh times, not screen refresh times. At 10 frames per second, the screen update time is longer than 1/10th of a second for scale factors 4 and 9. At scale factor 4, the display will be updated approximately every 220ms and, at scale factor 9, every 700ms. This is because the bilinear calculations take some time to complete for higher scaling factors.

In calibration mode, the sensor is set to 1 FPS, and 10 readings are taken over a 10-second period. These are then averaged, and the correction factors for each pixel are stored in

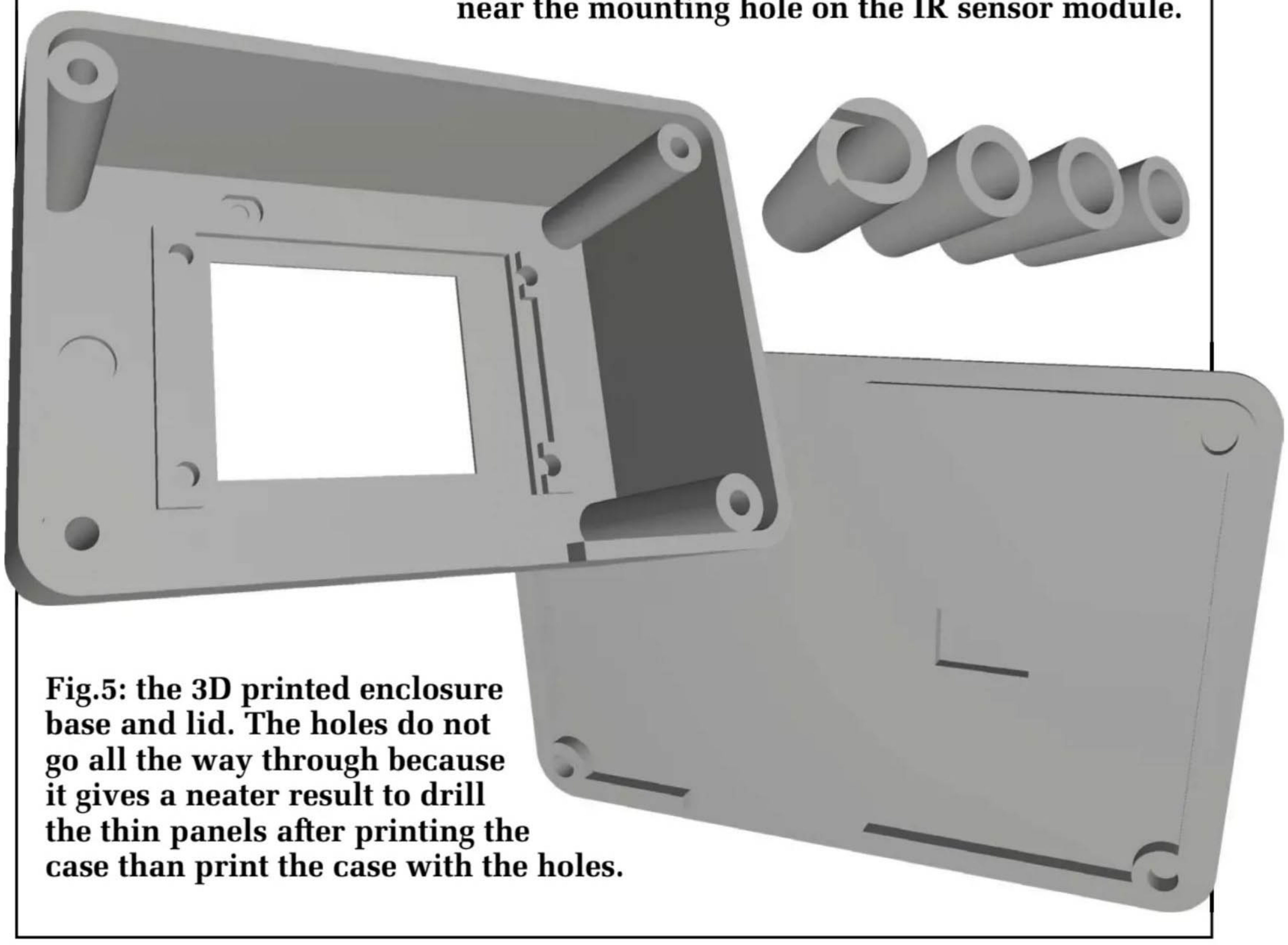
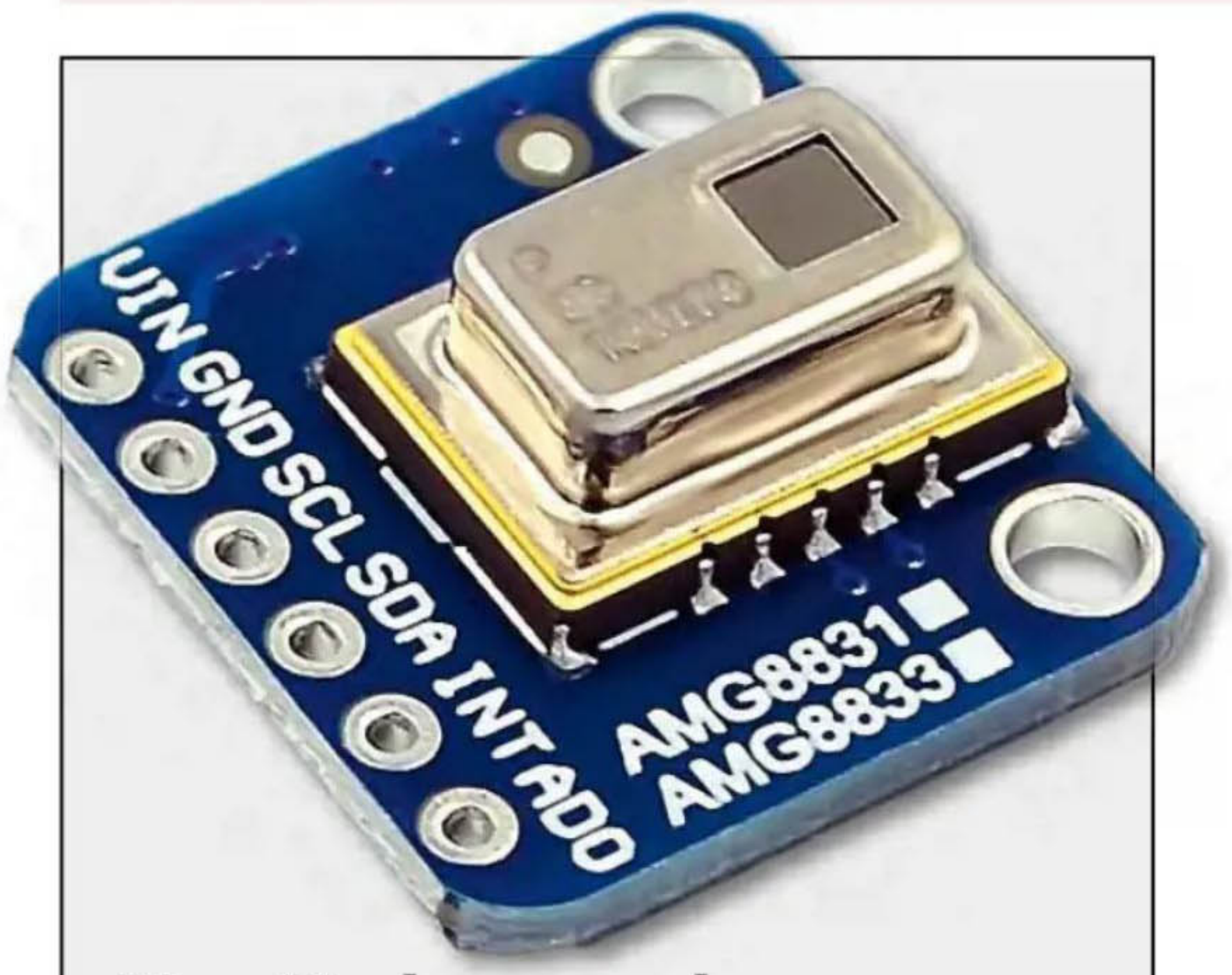


Fig.4: 3D-printed spacers are used rather than off-the-shelf types since we can make them exactly the right dimensions, and you can print them at the same time as the case. Note the cut-out in one to clear an SMD component near the mounting hole on the IR sensor module.

Fig.5: the 3D printed enclosure base and lid. The holes do not go all the way through because it gives a neater result to drill the thin panels after printing the case than print the case with the holes.

Parts List – Raspberry Pi Thermal Camera

1 double-sided PCB coded 04105231, 60 × 52.5mm from the *PE PCB Service*
1 Raspberry Pi Pico
1 3D-printed enclosure (body and lid)
4 3D-printed spacers
1 AMG8833 Grid-EYE IR sensor array breakout board module with pin order VIN, GND, SCL, SDA, INT and ADO **[AliExpress www.aliexpress.com/item/33012193094.html]**
1 1.8-inch 128×160 pixel SPI LCD TFT screen with ST7735 controller **[Tempero Systems TS-S006; eBay; AliExpress www.aliexpress.com/item/1005003797803015.html {1.8 inch option}]**
1 SPDT momentary PCB-mounting subminiature pushbutton switch (S1) **[Altronics S1493 or APEM TP32P0]**
1 39Ω 5% ¼W axial resistor
2 20-pin headers, 2.54mm pitch
2 20-pin header sockets, 2.54mm pitch
1 8-pin header socket, 2.54mm pitch
1 6-pin header socket, 2.54mm pitch
2 M2.5 × 20mm panhead machine screws and hex nuts
4 M3 × 25mm panhead machine screws and hex nuts
4 No.2 × 6mm countersunk head self-tapping screws



It's critical you purchase a module with the same output pin layout as the one shown above.

non-volatile memory. Good results are obtained by holding the sensor perfectly still 2-3cm from a white sheet of paper.

If the button is pressed during calibration, calibration is abandoned, and the correction factors are cleared. We recommend letting the sensor stabilise for at least one minute with power on before performing calibration.

Software tweaks

In the software, the constant 'Fahrenheit' can be set to 'true' to display temperatures in Fahrenheit rather than centigrade/Celsius.

The constant 'Minimum_span' sets the minimum temperature span for the display when there is little temperature variation across the whole display. This prevents wildly varying colours for minimal temperature changes. Lower values make the display more sensitive when there is an almost uniform temperature gradient.

Speeding up the refresh rate

The latest version of the PicoMite firmware **PicoMiteV5.07.06.uf2**) allows the CPU speed to be increased from the old maximum speed of 252000 to 378000 with the command:

```
Option CPUspeed 378000
```

This means that, with a scale factor of 4, the display will be updated approximately every 165ms rather than 220ms and, at scale factor 9, every 520ms rather than 700ms. However, note that this is 'overclocking' the RP2040 processor and it's possible that it won't work on every board or under all conditions. Still, most Pico boards should be capable of running at this speed.

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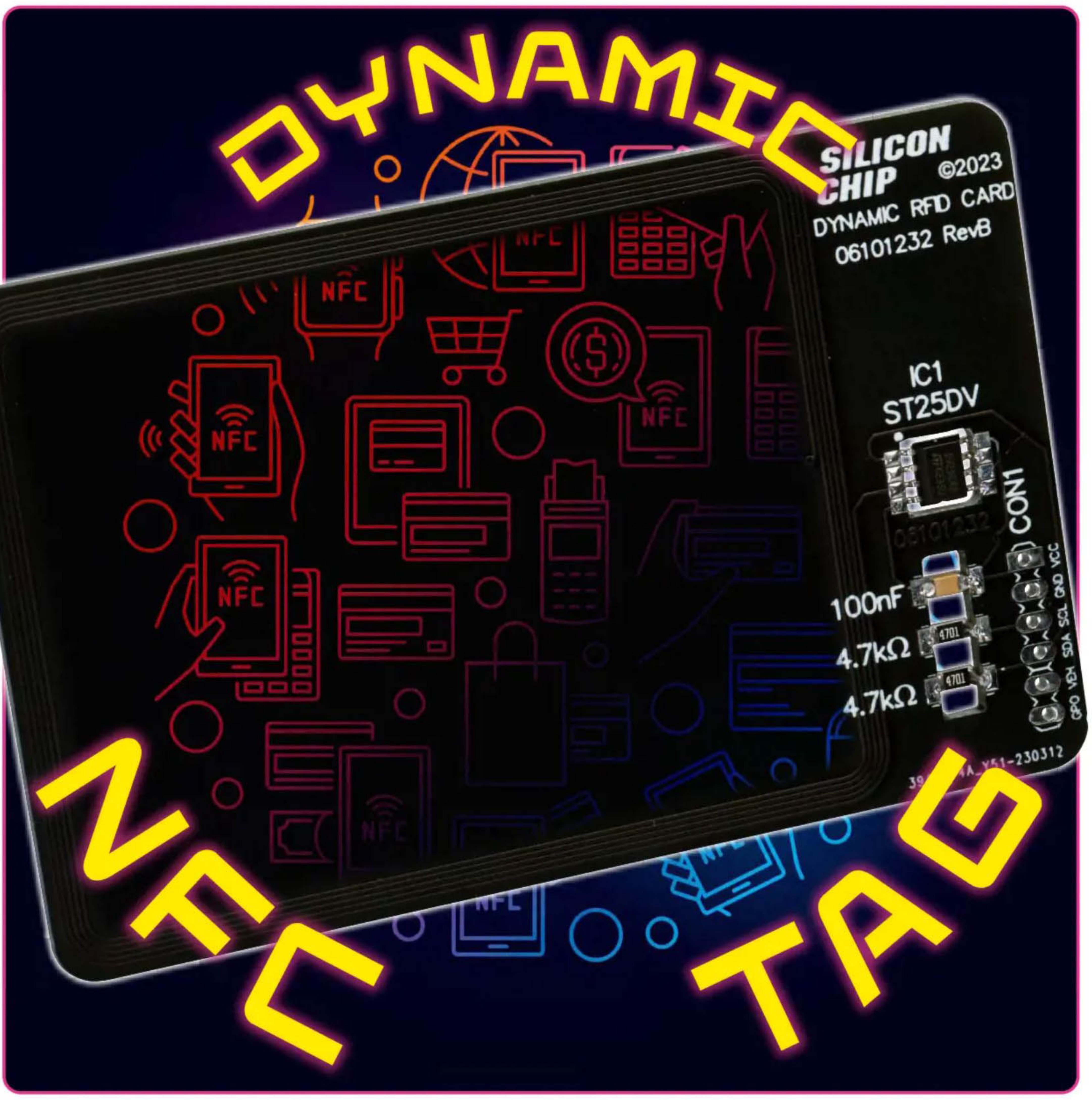
DYNAMIC NFC TAG



Dynamic NFC Tag Features

- Compact tag (22 × 31mm)
- Thin credit card/business card size tag (86 × 54mm)
- Arduino sketch and jig allows custom tags to be easily created
- Tags can also be written from apps

Supported NDEF Tag Types

- Text
- URI/URL (http:, https:, tel:, mailto: and many more)
- Wi-Fi network handover
- vCard
- MIME file types

Supported Chips

- ST25DV04K
- ST25DV04KC
- ST25DV16K
- ST25DV16KC
- ST25DV64K
- ST25DV64KC

Project by Tim Blythman

Near-field communication (NFC) devices have become widespread, especially for 'contactless' payments. The availability of dynamic NFC tags means you can now easily create your own custom NFC/RFID Tags. This article explains how to program NFC chips that can be used as smart business cards and more.

You likely have several NFC tags in your possession. Most bank cards and stored credit public transport cards use NFC technology. You might also hear them referred to as RFID or contactless cards.

NFC protocols allow communication over distances up to around 5cm using antennas transmitting and receiving at 13.56MHz. The NFC Forum is responsible for standardising NFC technology.

RFID is a broader term technology that includes NFC, also having systems that operate at 125kHz and around 900MHz.

It's now possible to create your own 'dynamic' NFC tags using a handful of components. 'Dynamic' means the tag's contents can be easily reprogrammed.

While you might be familiar with how easily NFC allows money to leave your bank account, NFC tags can also allow small amounts of data to be stored and transferred. With many mobile smartphones having NFC chips, we'll look at some apps that can work with NFC tags, including reading and writing.

Writing custom data to tags using a Raspberry Pi Pico microcontroller and the Arduino IDE is quite easy. Such tags can also be read back using the microcontroller too.

These custom tags can contain, for example, a vCard file. That format encapsulates the sort of information typically found on a business card. A programmed tag thus behaves like a virtual business card and can be 'taken' by simply reading it with an appropriate NFC reader, such as a mobile phone. The phone can import those contact details into an address book.

URIs (uniform resource identifiers) such as web addresses can also be written to a tag (a URI is a more general form of a URL, also known as a link). Customers can be directed to a website by tapping their mobile phone instead of manually entering a web address, similar to how QR codes are often used.

NFC technology

Jim Rowe covered an Arduino shield that uses NFC technology in an article from September 2019. That article briefly explained the history and technology behind NFC.

Despite being based on NFC technology, the shield from the 2019 article (which uses a PN532 NFC controller IC) will not work with these tags as they use different versions of the NFC standard. The PN532 can work with tags that comply with ISO14443A (type 2, 3 or 4 tags), while the tags we are using comply with ISO15693 (type 5 tags).

One of the great advantages of NFC is that the tag does not need its own power source. The reader creates an RF field at 13.56MHz that is picked up by the tag; it harvests energy from that to power its internal circuitry. Since the tag does not need a battery, it can be tiny. Tags the size of coins are commonplace, and smaller tags are possible.

As shown in Fig.1, the coils in the reader and tag effectively form an air-cored transformer, which limits the practical communications range.

Data is transferred when either the reader or the tag modulates the RF field. The reader can do this easily, as it generates the field, while the tag can do this by changing its RF impedance. The reader senses this through changes in the load it sees as it drives the RF field.

For this project, we're using a specific type of chip that provides the dynamic tag feature. Unfortunately (!), this means that you won't be able to hack into your bank card and trick it into thinking you have more money than you do!

Tap phone here for real-time bus updates
NFC
translink

This timetable pole at a bus stop in Queensland includes an NFC tag with an NDEF URI record. It directs users to a web page displaying live bus departure times for the bus stop.

Terminology

A reader is a device that generates an RF field and can use this to communicate. You might also hear the term emitter used, since this device emits the RF field.

'Tags' are simply devices that can communicate with an NFC reader. They are typically implemented by combining a tag-capable chip (which contains some non-volatile memory) with an appropriate antenna and perhaps a few passive components.

The antenna is often little more than a printed foil loop, similar to a PCB trace antenna, but on a thinner substrate. We tried a few variations on custom antennas that we'll describe later.

Some tags have an internal EEPROM, including the chips we are using, in which case the reader might be able to write to the tag and change its contents.

Portable tags are commonly found in the form of a card or a keyfob that can be easily carried around. You might also see fixed tags, often in a more robust enclosure to prevent damage.

The NDEF (NFC Data Exchange Format) specifies headers and other data that indicate what sort of data the tag carries; these are the sort of tags this project allows. NDEF tags are only a subset of NFC, and other types of NFC tags exist.

The software we have written allows you to explore NDEF data at a low level. Briefly, there is a Capability Container (CC), which indicates that the tag contains NDEF data and the amount of available storage space.

This, in turn, points to an NDEF message, which can contain one or more NDEF records. An NDEF record is roughly analogous to the contents of a single file, although the NDEF message doesn't have a file system as such.

While NDEF does allow multiple messages and records on a tag, for simplicity, our software only writes one message containing one record at a time, although it can read multiple records.

The ST25DV IC

Dynamic tags are those tags that can be easily reprogrammed. In this project, we will use members of the ST25DV family from ST Microelectronics. These parts include the RF interface needed to implement NFC, an EEPROM and an I^{2}C interface that allows their internal EEPROM to be modified and thus present changing data to an NFC reader.

Many tags, including those from the ST25DV family, can also be written over the RF interface, provided that the 'reader' also has write capabilities, as many do. One of the apps we tried (from ST Microelectronics) can write to these chips.

You don't necessarily need to use the I^{2}C interface to work with these chips, but it is an easy way to do so.

In fact, many readers (especially those on mobile phones) can also emulate tags; this is the basis of how 'pay by phone' technology works. The phone emulates a virtual contactless credit card.

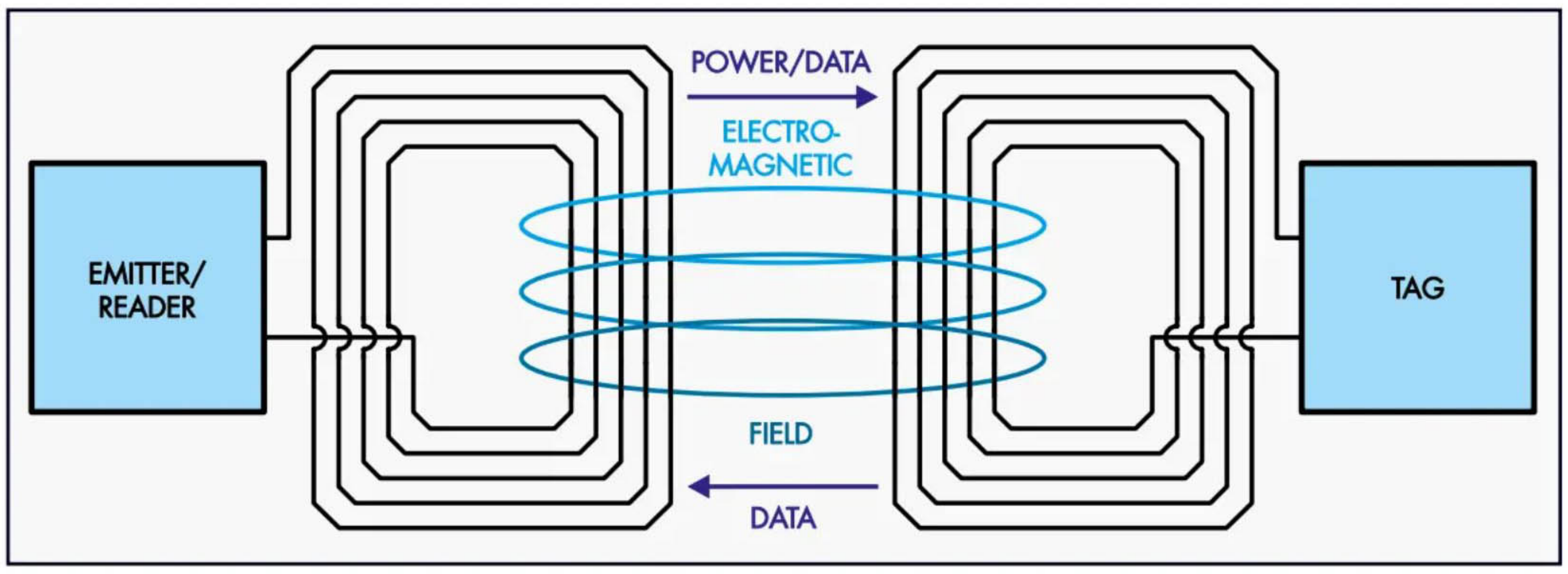


Fig.1: with NFC, an unpowered device (the tag) is powered by the received RF field and can transmit data back to a reader or emitter by modulating that field.

The specific chips we are using are the ST25DV04K, and they have 512 bytes of EEPROM space (with maybe a dozen bytes taken up by the NDEF headers). Data such as that found in brief text files is an excellent candidate for being passed around, including the vCards mentioned earlier.

Similar chips from the same family can hold up to 8kB, which will also work with all the software we will discuss, but we haven't concentrated on them mainly because of how long it takes to transfer that much data over an NFC link.

Possible uses

Some people will find it convenient to program tags once and then use them as smart business cards or to pass other information around.

For example, you might provide a tag to allow guests to connect to your Wi-Fi network when they visit. You could attach a tag to an object containing text information about that object.

You might have heard of 'smart posters' being used in advertising. These are nothing more than printed posters accompanied by a tag that provides information beyond what is printed on the poster.

One use we have seen 'in the wild' is a tag at a bus stop. The tag is enclosed in a sturdy plastic shell and attached to the post that holds up a printed timetable (see photo). This is a simple but practical application.

This tag contains a URI NDEF message that points to a web page providing live bus departure times for that specific stop, supplementing the fixed information on the printed timetable.

Screen 1 shows a scan of this tag by one of the apps we will discuss later. It also uses a chip from ST Microelectronics (but a different one).

We have written an Arduino program that can add several types of records to these cards. As well as the vCards and URIs mentioned earlier, it can also create simple text file records and Wi-Fi 'handover' records. Such a record simply contains sufficient information (SSID name, password and security type) to allow a device such as a mobile phone to connect to a Wi-Fi network.

Another NDEF record type is the so-called MIME (Multipurpose Internet Mail Extension) type. The MIME standard was developed for email file attachments and carries information about a file's type.

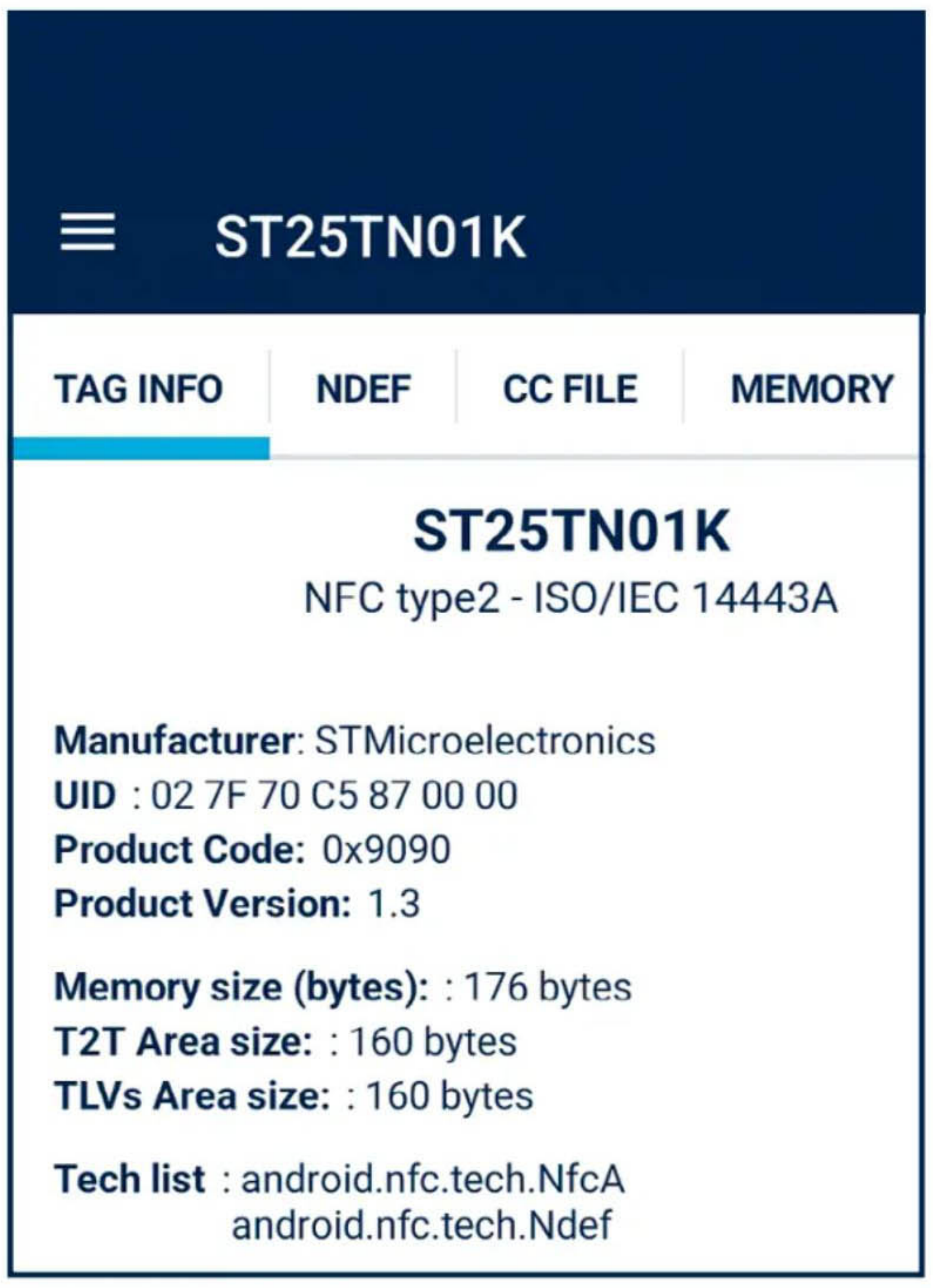
The vCard and Wi-Fi handover record types are simply MIME records of a specific type ('text/vcard' and 'application/vnd.wfa.wsc', respectively).

Thus, a MIME type record could be used to describe anything that could be considered a file, although it would have to fit in the available space on the tag. The receiving device would also need to know what to do with it; we found this was often not the case, even for common file types.

Also, when we uploaded some 'large' files to the 8kB ST25DV64K chips, they took many seconds to be downloaded by a reader and often appeared not to be working due to this delay.

On the other hand, vCards, Wi-Fi handover records or URIs (in the form of web addresses or email addresses) are widely recognised and will be the most useful types for custom tags.

With that out of the way, we'll show you how to construct a Tag using these dynamic tag chips, then use our Arduino software to program them for a specific use.



ST25TN01K

NFC type2 - ISO/IEC 14443A

Manufacturer: STMicroelectronics
UID : 02 7F 70 C5 87 00 00
Product Code: 0x9090
Product Version: 1.3

Memory size (bytes): : 176 bytes
T2T Area size: : 160 bytes
TLVs Area size: : 160 bytes

Tech list : android.nfc.tech.NfcA
android.nfc.tech.Ndef

Screen 1: an ST25 NFC Tap app scan of the bus stop tags shown in the photo. It has a much smaller capacity than the tags we are using, but still enough for a URI pointing to a web page.

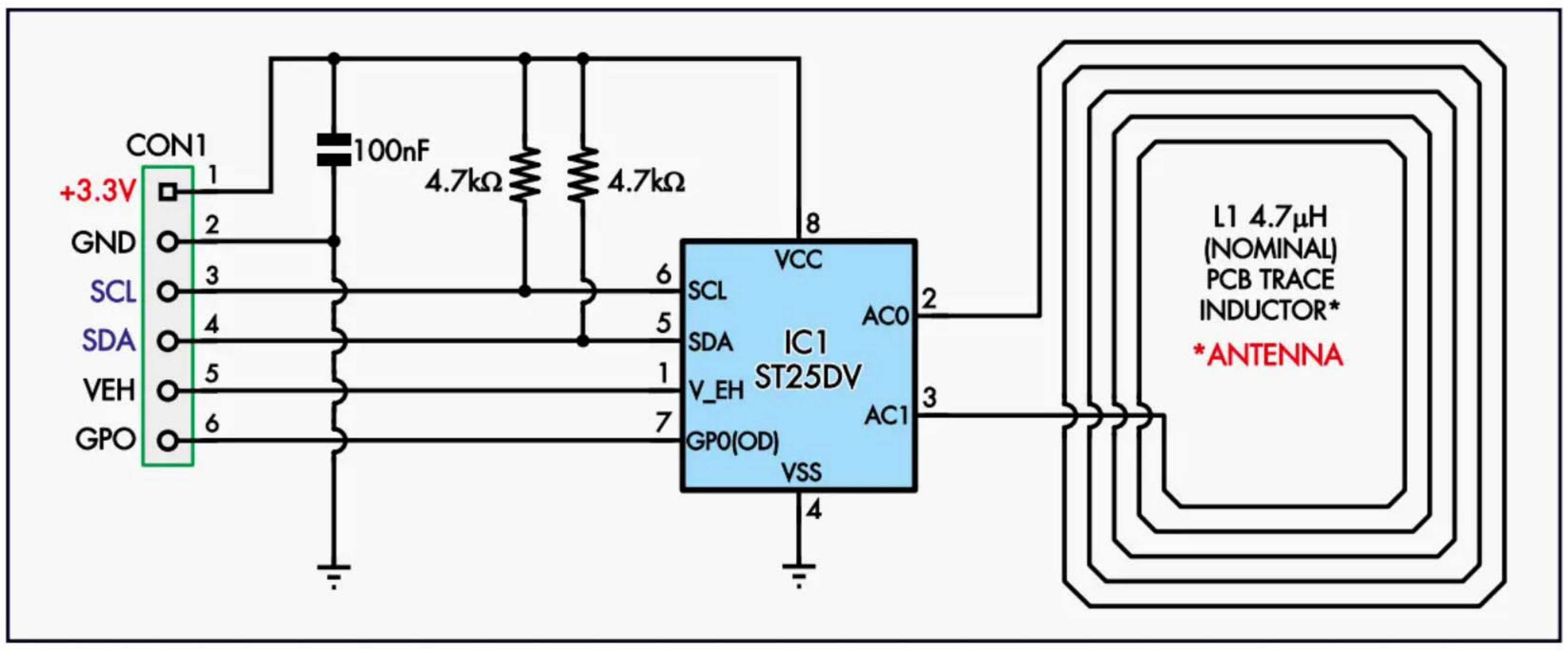


Fig.2: the circuit is very simple and, as you can see from our photos, it's possible to create it on a small breakout board. Other variants of tag chip IC1 have other functions broken out on more pins, but they are in packages that are difficult to hand-solder, such as WLCSP (wafer-level chip scale package).

We'll also show how to create Tags using various antennas, followed by using several apps to interact directly with the Tags over the RF interface, including reading and writing to them.

PCB tags

Fig.2 shows the schematic of our small PCB-based tags; IC1 is the chip that implements the dynamic tag function. It could be one of several chips from the ST25DV family, but we used the ST25DV04K variant for most of our testing, and that is what we specify in the parts list.

We have developed two different PCBs that implement this same basic circuit (see Fig.3 and Fig.4).

CON1 provides a breakout for all the pins of IC1 except those that connect to the antenna. The two resistors are the pullups needed for the I^2C SDA and SCL lines, while the 100nF capacitor provides supply bypassing when the chip is powered from CON1.

Pins 2 and 3 (AC0 and AC1) connect to a PCB trace antenna. IC1 has an internal tuning capacitance of 28.5pF, meaning that an inductance of 4.7µH is needed for resonance at 13.56MHz.

The larger PCB has five turns for the antenna, while the smaller PCB has fourteen turns, seven on each side. In practice, we found that the circuit wasn't too fussy about the exact coil dimensions. Later, we'll discuss some of the alternative coils that we tried.

The remaining pins on IC1 are VEH and GPO. The GPO pin is an open-drain output that can be programmed to drive its output low under certain conditions, such as while an RF signal is being received, or a write is being performed to the internal EEPROM.

The VEH pin (also when appropriately programmed) can deliver an unregulated voltage harvested from the external RF field, when available. In practice, we found this could be up to about 4V at up to 10mA. Naturally, this will depend on the reader and other factors, such as the antenna efficiency.

In one simple test, we hooked a light-emitting diode (LED) directly between the VEH and GND pins. After changing the appropriate registers to allow energy harvesting to operate, we got it to light up (when in a reader's RF field).

A simple tag (accessible by RF only) could consist of little more than the IC and an appropriate antenna. The passives are only needed if the I^2C interface is required.

Other tags

Since the tag chips can be programmed by RF as well as I^2C, it's possible to create a tag with nothing more than a chip and an antenna. You also could set up a rig using an SOIC socket of the correct width to program the chips before soldering them to an antenna.

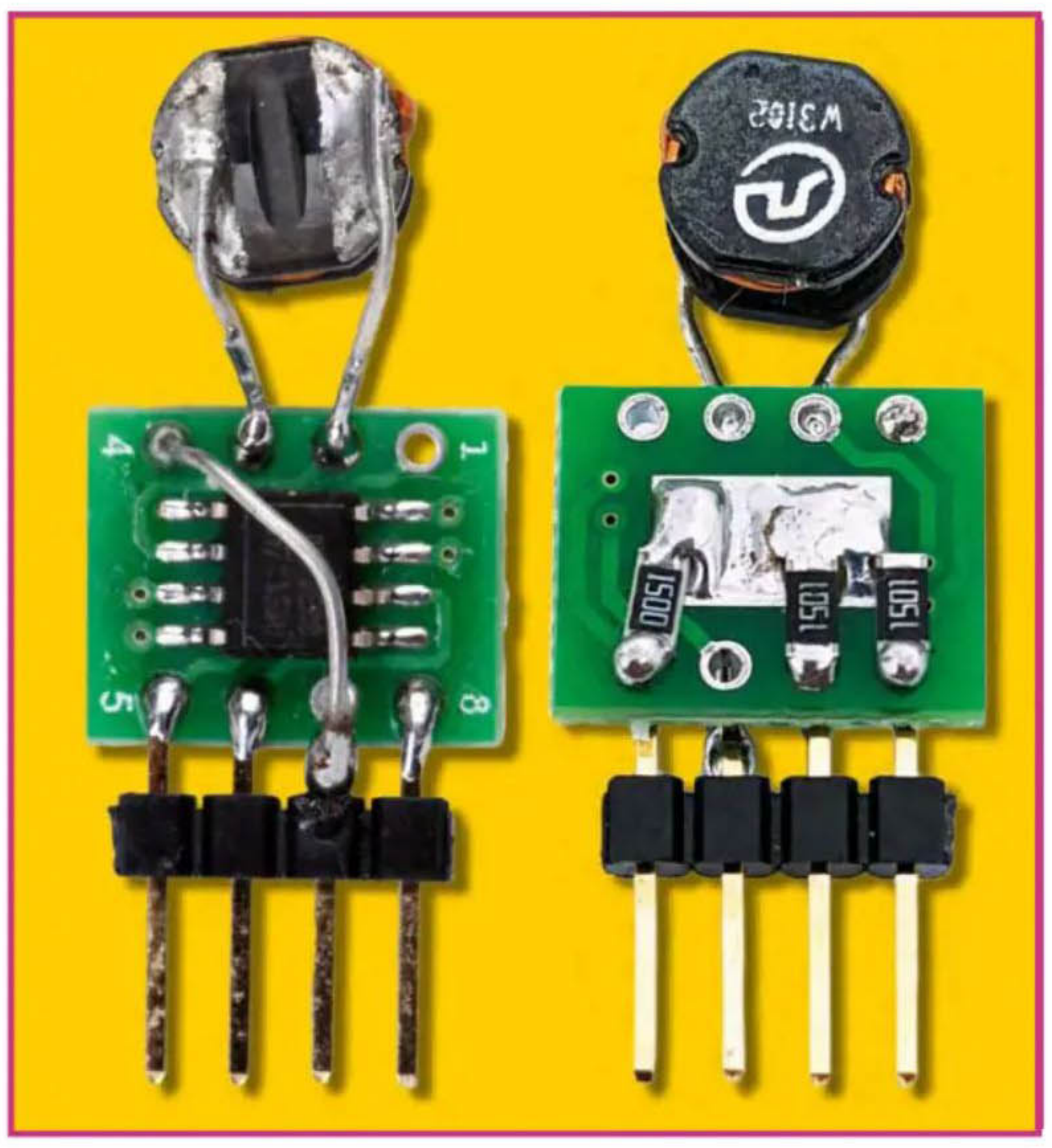
We even used one of our smaller PCBs (populated with everything except the chip) as a programming rig with the trick of holding the chip in place using a clothes peg. That was sufficient to allow testing of the tag via its RF interface, too.

The photos show a few of the prototypes we created to see whether it was possible to make a workable antenna without a PCB. As you can see, the answer is just about anything, within reason.

The photo opposite shows our first prototype, based on a small SOIC-8 to DIP-8 IC adaptor PCB. The antenna is actually a 6mm SMD inductor that is designed for this application. This prototype was great for testing how things should work, including the I^2C interface.

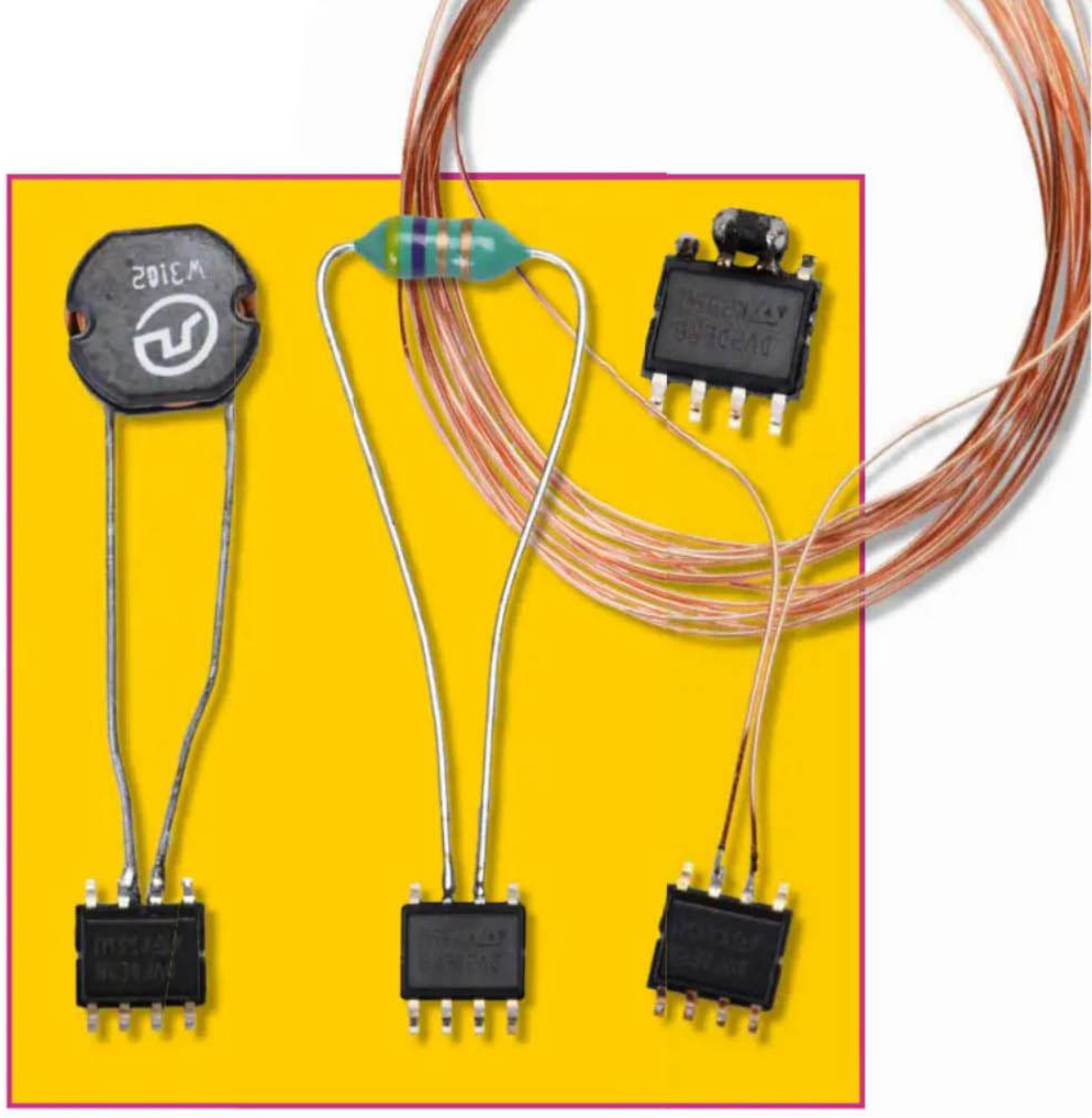
The photos to its right shows some antenna-only designs, including the design that inspired our first PCB. It is simply fourteen loops of enamelled wire soldered to the AC0 and AC1 pins of a tag chip. The diameter of the coils is just over 2cm, using a little over a metre of wire.

This set also shows a circuit with an axial leaded inductor with a



◄ **Our prototype Tag is constructed on a SOIC-8 breakout board and uses a 4.7µH wirewound inductor as the antenna. The passive components are on the back of the PCB, and the circuit is practically identical to our final designs.**

Connecting an antenna to pins 2 and 3 of the IC is sufficient to create a functional Tag. The antenna can be as simple as a 4.7µH inductor or many turns of enamelled copper wire. The wire antenna shown here uses just over 1m of wire. Be sure to strip the enamel from the ends of the wire before attempting to solder it. ►



nominal 4.7µH inductance, as well as the wirewound inductor seen in the previous photo. We also tried a tiny (M2012/0805) SMD inductor, shown in the upper right corner, but the reader did not pick it up.

This correlation between size and sensitivity also extended to the larger tags, with the larger PCB design being the most sensitive. We judged this simply on the distance from which the tag could be detected by the reader, being nearly 5cm for the larger PCB design.

Another reason the smaller SMD inductor didn't work, besides its size, might be that it has a shielded construction. Larger shielded inductors are also available; avoid using them, as they will not work well as antennas.

If you build a Tag without the I^{2}C interface, you won't be able to use the Arduino Programming Rig that we will describe later. You will only be able to program the Tags using apps installed on a mobile phone or a similar reader.

PCB designs

The two Tag PCBs are shown in Fig.3 and Fig.4 and the photos overleaf. The smaller PCB is coded 06101231 and measures 22 × 31mm, while the larger PCB is coded 06101232 and measures 85.5 × 54mm – both are available from the *PE PCB Service*.

The usual SMD tools and supplies will be adequate for building the PCB-based tags. This includes solder, flux paste, tweezers, good lighting and a fine-tipped iron. Fume extraction is recommended when working with flux paste due to the amount of smoke it generates.

For the smaller PCB (06101231), assembly is straightforward. Apply flux to the pads of the four SMD components and rest each in place. IC1 is the only polarised part, so check that the chamfer along one edge (best seen from the end of the chip) aligns with the marking on the PCB.

Tack one lead of each component and ensure the remaining leads are within their respective pads. Then solder the remaining leads and refresh the first leads. Check for solder bridges and use solder-wicking braid to remove them.

The larger PCB (coded 06101232) is designed to have the components sit inside slots so that they are no thicker than the PCB itself. We used a silicone soldering mat to align the components vertically within the slots. Rather than resting on surface pads, the parts are soldered to exposed edges of the plated-through holes. The photos above show the final result.

IC1 is very close to the same thickness as the PCB (1.6mm), while the passives are much thinner. This is an experimental technique, so it is best suited to constructors with some SMD soldering experience.

Before soldering the components, check the pads for copper swarf or burrs, as some may be left from the milling process during PCB manufacture. We found it wasn't necessary to remove any burrs unless they could cause a short circuit or interfere with component placement.

The technique is similar to regular SMD work in that each component should be initially secured by one lead. Use tweezers to locate the part before tacking, after which the remaining leads can be soldered.

You might need to build up a small fillet of solder to ensure a mechanically sound connection. Inspect the joints and use flux and solder-wicking braid as necessary to tweak the location and amount of solder.

For IC1, first tack the leads along one edge. Then flip the PCB over and gently bend out the IC leads along the other edge to be closer to the PCB pads. Solder these leads to their corresponding pads.

We found that the best results came from using a generous amount of solder and flux. We then applied solder braid to the PCB pads only to draw off excess solder, relying on surface tension to keep a suitable amount of solder connecting the lead.

If you like, a pin header can be soldered to CON1 on either PCB, but if you only intend to program the tag once, simply holding the header in place should be sufficient. We've offset the holes slightly to give a firm friction fit.

If you wish to add some polish to your Tag PCBs, you could glue paper or cardboard (such as your own paper

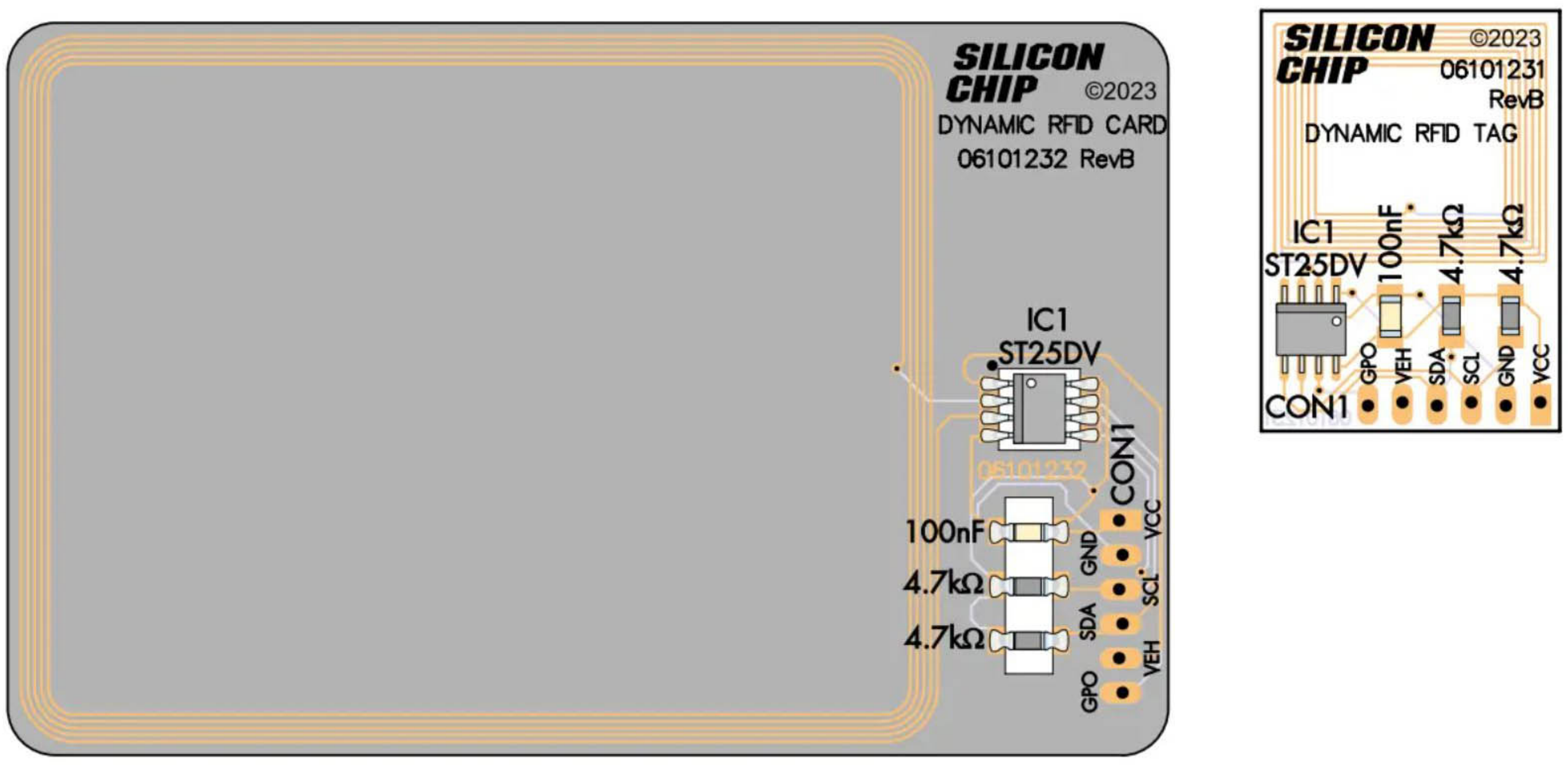


Fig.3 and Fig.4: assembling the smaller PCB is pretty straightforward. The larger PCB is a little trickier as the components are nestled into cutouts. Still, if you've done any SMD soldering, you should be able to use similar techniques to do that.

SILICON CHIP
©2023
DYNAMIC RFID CARD
06101232 RevB
IC1
ST25DV
CON1
100nF
4.7kΩ
4.7kΩ
39454414A_Y51-230312

The larger card Tag PCB has cutouts so that the components are internal and don't increase the overall thickness; the SOIC IC is nearly exactly the same thickness as the PCB! You'll need careful use of flux and solder wick to fit the components. You can create a more polished look by gluing paper or cardboard (or sticking a sticker) to the front and back of the PCB.

business card) to the front and back of the PCB. You could even get custom stickers of the right size made.

The programming jig

Our programming jig is simple and just requires a Raspberry Pi Pico (or Pico W) with four connections to CON1 on the Tag PCB. We used the Arduino IDE to write the program, as a good Arduino library is available to work with these chips.

If you want to modify or work with our code and don't have the Arduino IDE installed, download and install it from: **www.arduino.cc/en/software**

Still, you don't need the Arduino IDE to try our sketch out. Simply hold down the white BOOTSEL button on the Raspberry Pi Pico while plugging it into a computer. Then copy the **0610123A.UF2** file to the drive that appears; it's typically named 'RPI-RP2'. The file is available from the July 2024 page of the *PE* website: **https://bit.ly/pe-downloads**

If you want to program tags beyond what our sketch can do or tweak the sketch, you will need the SparkFun ST25DV64KC library in addition to the Arduino IDE. This will also work with other chips, including the -04K, -16K, -64K, -04KC and -16KC variants.

We've included a copy of the version we used in the software download. It can also be found by searching for 'st25dv' in the Arduino Library Manager. As well as the SparkFun library, this will show a library from ST Microelectronics, but that one appears to be designed to work with Arduino boards based on their (STM) microcontrollers and not the Pico.

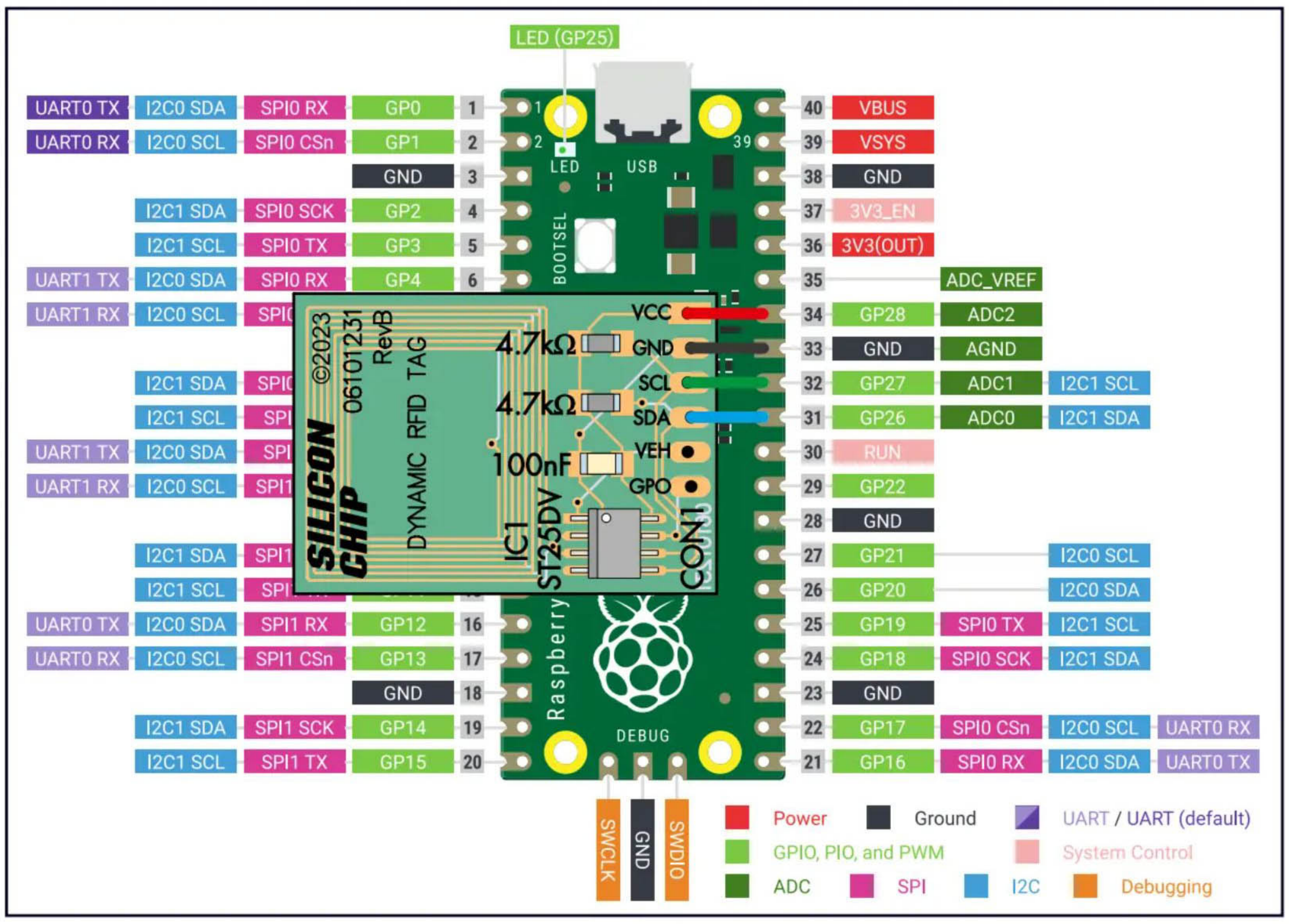
We've designed the interface to use four adjacent pins on the Pico. These correspond to the four I^2C pins on CON1 of either PCB. Pin GP28 is driven high as an output to provide 3.3V. Next to it is a ground pin followed by pins GP27 and GP26 to provide I^2C SDA and SCL, respectively.

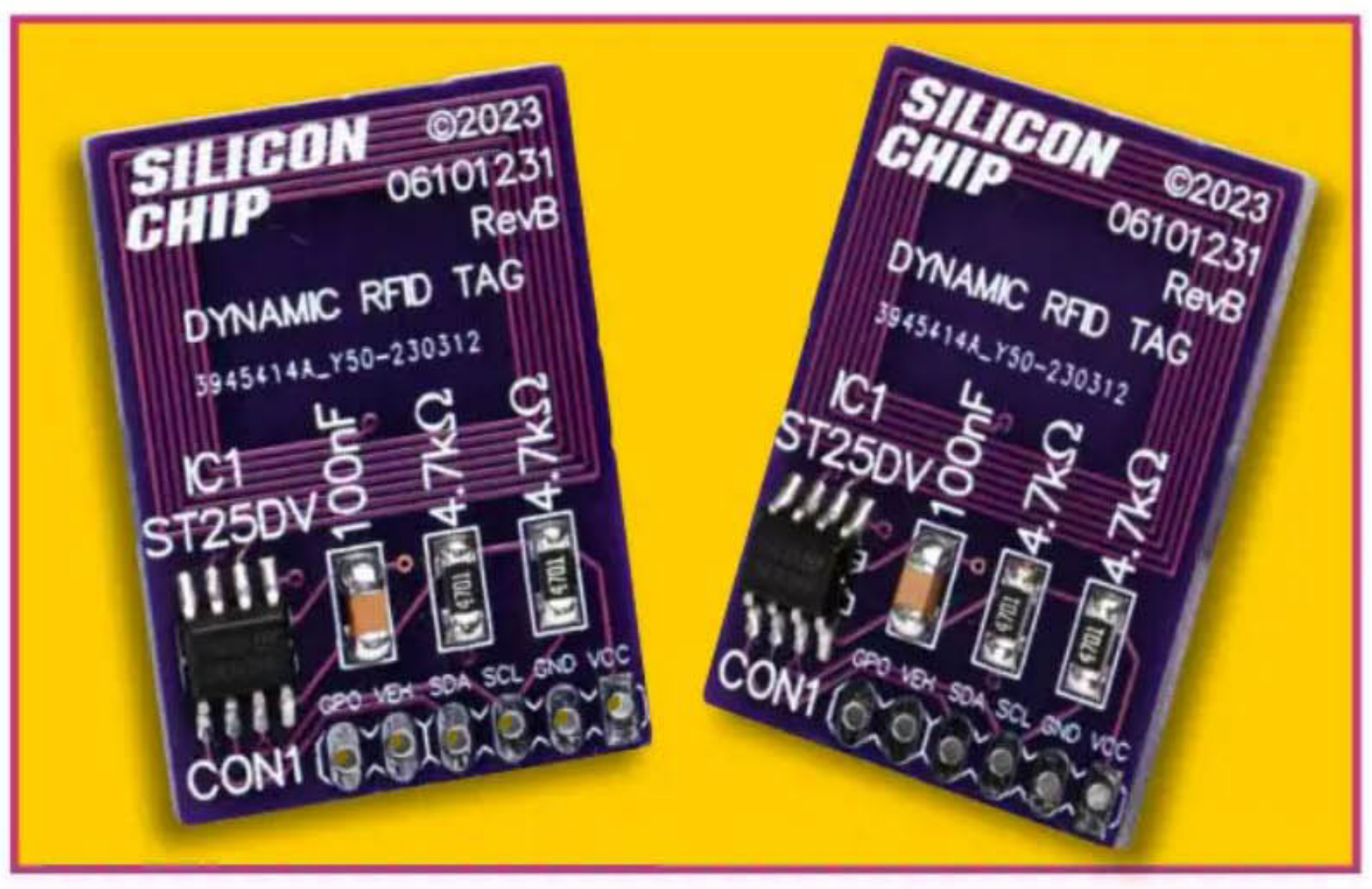
Fig.5 shows the connections needed. The simplest way to achieve this is to solder a four-way pin header to the Pico, allowing the Tag to be friction fitted. However, you could use a breadboard or even solder wires if you like.

The RF and I^2C interfaces can coexist, but note that communication cannot occur on both simultaneously. So you can leave the Tag connected to the programming jig while testing the Tag with a reader, as long as you don't attempt to read or write at the same time.

To control the programming jig from your computer, you will also need a serial terminal program, such as TeraTerm on Windows or minicom on Linux. The Arduino IDE's serial monitor has limited functionality and will work for some commands, but not all. Verify that your serial terminal program uses CR or CR/LF as the line ending. The program checks for CR and ignores LF.

Fig.5: the wiring from the Pico to the Tag is simple; you can solder a four-pin header to the Pico and plug the Tag onto that. You can also use a breadboard if you have soldered full-length headers to your Pico. ►


LED (GP25)
UART0 TX I2C0 SDA SPI0 RX GP0 1
UART0 RX I2C0 SCL SPI0 CSn GP1 2
GND 3
I2C1 SDA SPI0 SCK GP2 4
I2C1 SCL SPI0 TX GP3 5
UART1 TX I2C0 SDA SPI0 RX GP4 6
UART1 RX I2C0 SCL
I2C1 SDA
I2C1 SCL
UART1 TX I2C0 SDA
UART1 RX I2C0 SCL
I2C1 SDA
I2C1 SCL
UART0 TX I2C0 SDA SPI1 RX GP12 16
UART0 RX I2C0 SCL SPI1 CSn GP13 17
GND 18
I2C1 SDA SPI1 SCK GP14 19
I2C1 SCL SPI1 TX GP15 20
40 VBUS
39 VSYS
38 GND
37 3V3_EN
36 3V3(OUT)
35 ADC_VREF
34 GP28 ADC2
33 GND AGND
32 GP27 ADC1 I2C1 SCL
31 GP26 ADC0 I2C1 SDA
30 RUN
29 GP22
28 GND
27 GP21 I2C0 SCL
26 GP20 I2C0 SDA
25 GP19 SPI0 TX I2C1 SCL
24 GP18 SPI0 SCK I2C1 SDA
23 GND
22 GP17 SPI0 CSn I2C0 SCL UART0 RX
21 GP16 SPI0 RX I2C0 SDA UART0 TX
LED
USB
BOOTSEL
Raspberry Pi
DEBUG
SWCLK
GND
SWDIO
©2023
06101231
RevB
DYNAMIC RFID TAG
SILICON CHIP
IC1
ST25DV
CON1
4.7kΩ
4.7kΩ
100nF
VCC
GND
SCL
SDA
VEH
GPO
Power
Ground
UART / UART (default)
GPIO, PIO, and PWM
System Control
ADC
SPI
I2C
Debugging


SILICON CHIP
©2023
06101231
RevB
DYNAMIC RFID TAG
IC1
ST25DV
100nF
4.7kΩ
4.7kΩ
CON1

The smaller Tag is a straightforward SMD design. The staggered holes on CON1 allow a header to be temporarily friction-fitted for programming. That avoids the need to fit the bulky headers permanently.

Programming Tags

After connecting to the Pico's virtual serial port with the terminal program, you should see the main menu (see Screen 2). Check that the message 'ST25 found on I2C' is shown before proceeding.

If you don't see it, check your connections and use the '~' command to reboot the Pico if necessary, forcing it to test for communication again.

Each of the commands consists of one or two letters (followed by Enter), after which you may be prompted for additional parameters depending on the specific command. Screen 3 shows the output of the basic 'i' and 'c' commands, while Table 1 details the available commands.

The 'i' command provides information about the tag chip's serial number, which can be used to deduce the part number. The part number includes the EEPROM size in kilobits; the ST25DV04K part shown has 4 kilobits (512 bytes) of EEPROM.

The 'c' command interprets any NDEF data that is present. What is shown in Screen 3 is typical for a tag with a single URI entry, in this case, a link to the Silicon Chip website.

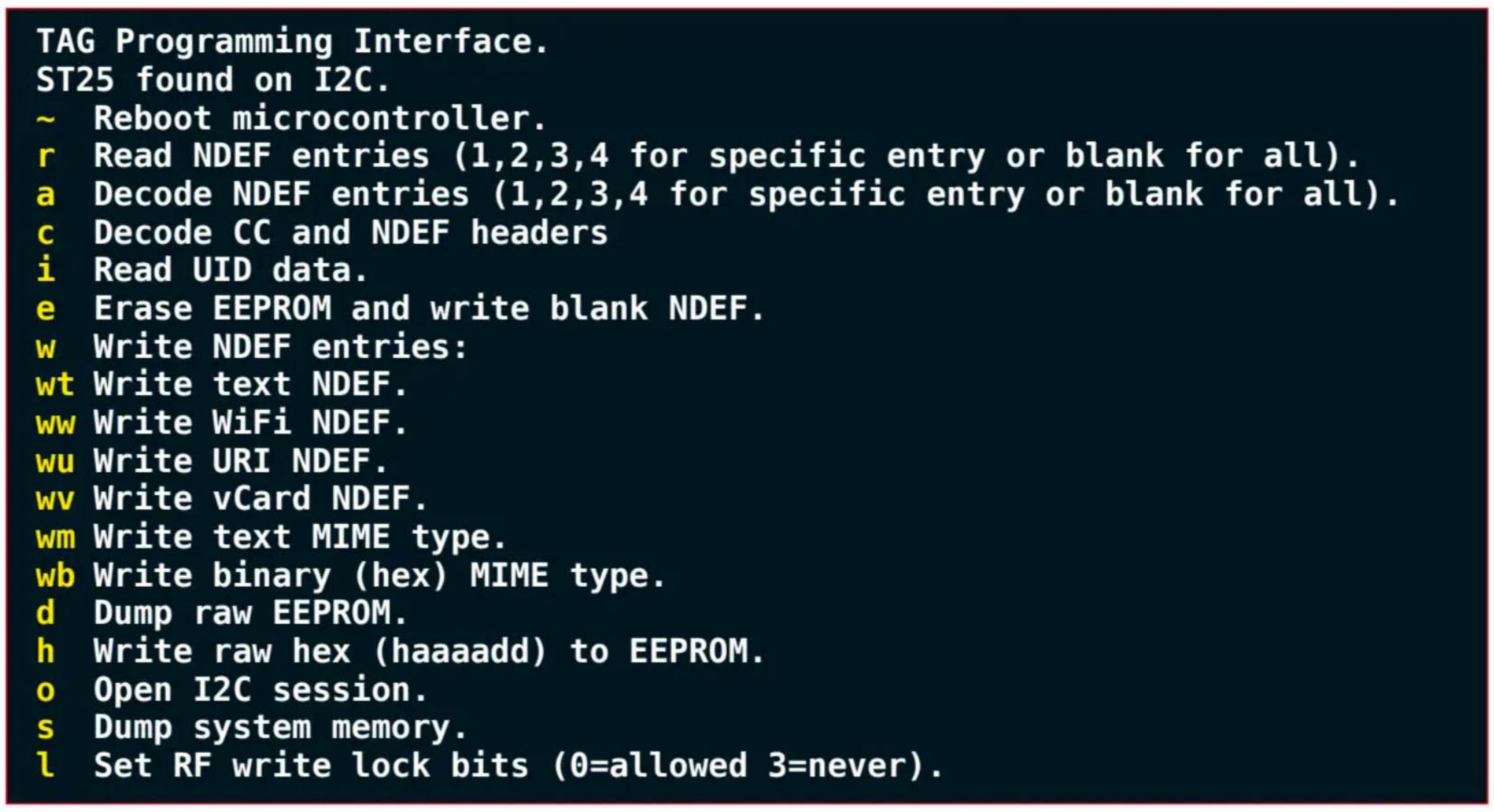
Screen 4 shows a raw dump of the EEPROM contents in both ASCII (at left) and hexadecimal (at right). The link text is visible, preceded by some header data. You don't need to know the header formats, as the library can generate them.

The minimal steps for creating a custom tag start with the 'e' command to erase the tag contents if it is not blank. While the chips start out empty, the library depends on the appropriate capability container entry existing, which is also added by the 'e' command.

Follow that with one of the 'w' commands to write an appropriate NDEF entry. The 'wt' (text) and 'wu' (URI) options prompt for a single entry to be written to the tag. The 'ww' command asks for the Wi-Fi name (SSID), password, authentication and encryption types.

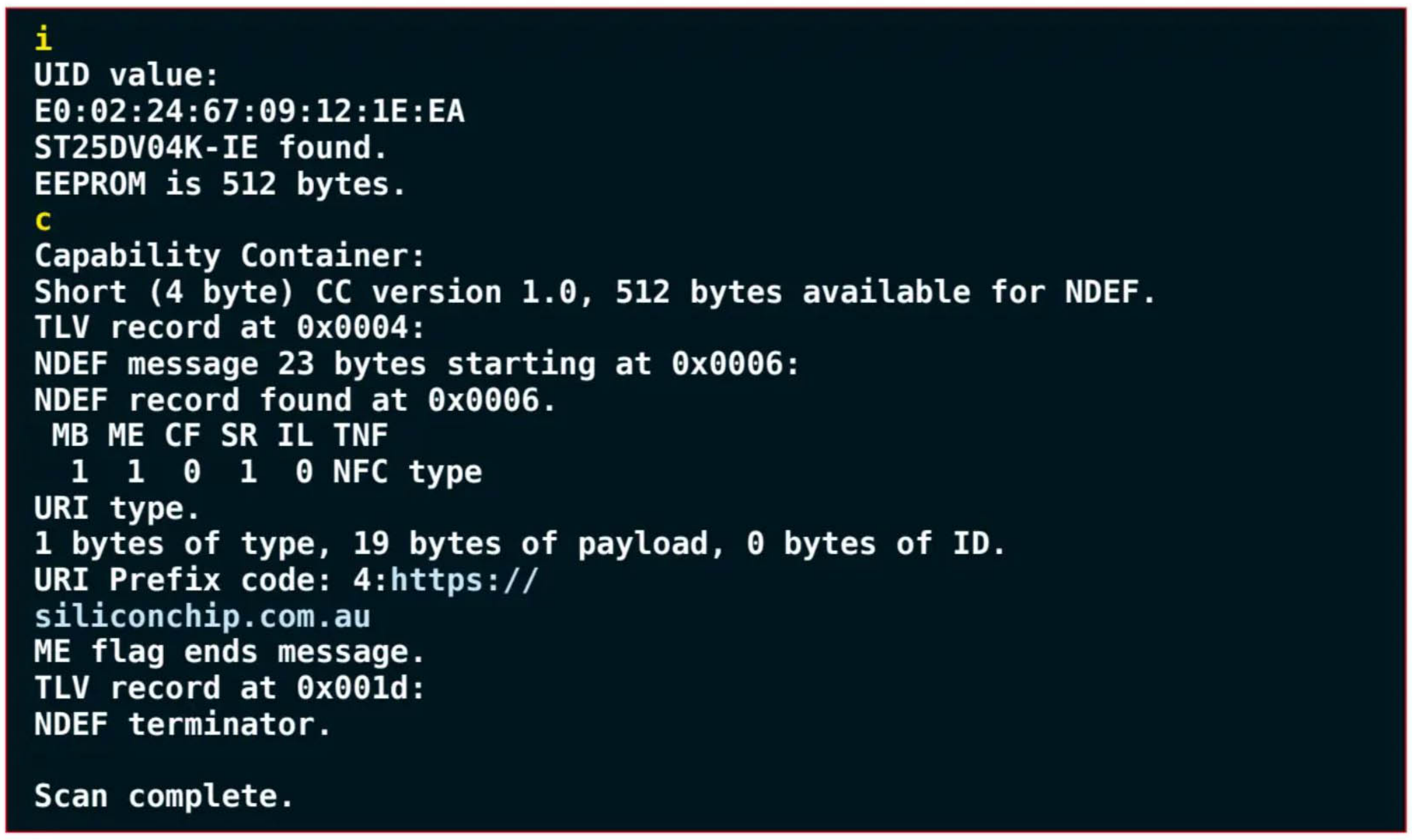
The two MIME commands, 'wm' and 'wb', allow a MIME type to be specified, with the file contents following. The 'wm' option can handle text input, including control codes like CR (carriage return) and TAB. Press Ctrl-D or Ctrl-Z (end-of-file) to complete these entries; Ctrl-C or Escape can be used to cancel.

The 'wb' command expects bytes to be entered as pairs of hexadecimal digits. Single hexadecimal digits can be entered if a space separates them. The same Ctrl-D or Ctrl-Z sequence completes the file.



```
TAG Programming Interface.
ST25 found on I2C.
~  Reboot microcontroller.
r  Read NDEF entries (1,2,3,4 for specific entry or blank for all).
a  Decode NDEF entries (1,2,3,4 for specific entry or blank for all).
c  Decode CC and NDEF headers
i  Read UID data.
e  Erase EEPROM and write blank NDEF.
w  Write NDEF entries:
wt Write text NDEF.
ww Write WiFi NDEF.
wu Write URI NDEF.
wv Write vCard NDEF.
wm Write text MIME type.
wb Write binary (hex) MIME type.
d  Dump raw EEPROM.
h  Write raw hex (haaaadd) to EEPROM.
o  Open I2C session.
s  Dump system memory.
l  Set RF write lock bits (0=allowed 3=never).
```

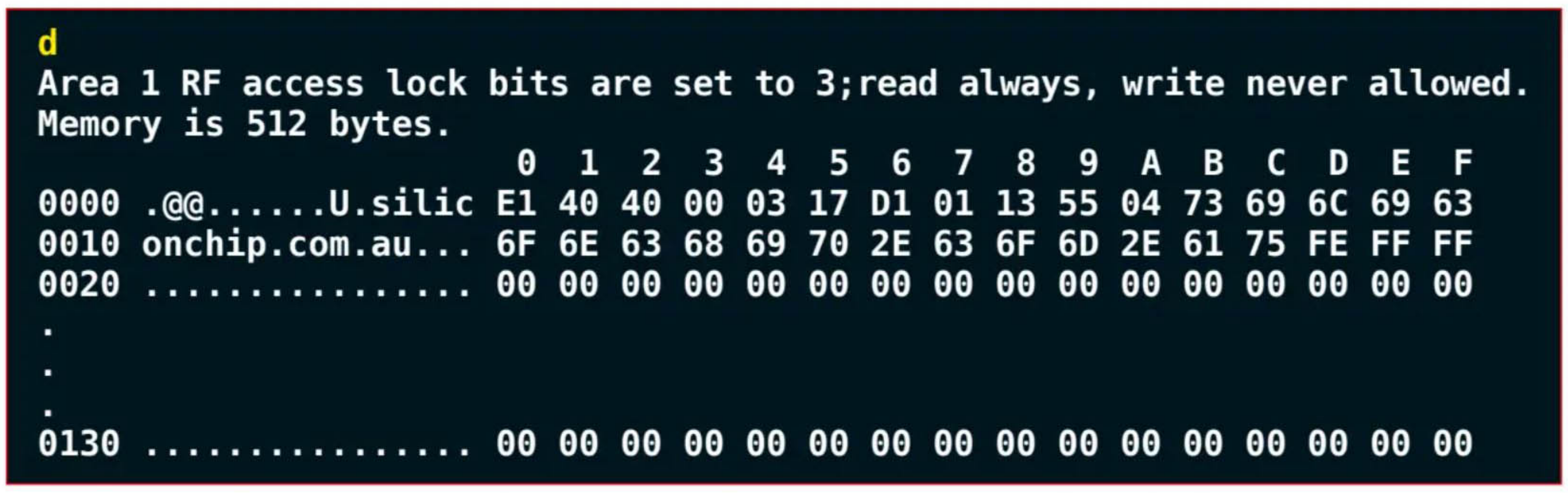
Screen 2: the main menu of our programming jig software has the options shown here. While there are quite a few commands, many are to explore the structure of the data on the Tags and are not needed to create your own Tags.



```
i
UID value:
E0:02:24:67:09:12:1E:EA
ST25DV04K-IE found.
EEPROM is 512 bytes.
c
Capability Container:
Short (4 byte) CC version 1.0, 512 bytes available for NDEF.
TLV record at 0x0004:
NDEF message 23 bytes starting at 0x0006:
NDEF record found at 0x0006.
 MB ME CF SR IL TNF
  1  1  0  1  0 NFC type
URI type.
1 bytes of type, 19 bytes of payload, 0 bytes of ID.
URI Prefix code: 4:https://
siliconchip.com.au
ME flag ends message.
TLV record at 0x001d:
NDEF terminator.

Scan complete.
```

Screen 3: the 'i' command checks what type of tag chip you have and its capacity, while the 'c' command allows you to verify that the NDEF headers are present and correct.



```
d
Area 1 RF access lock bits are set to 3;read always, write never allowed.
Memory is 512 bytes.
                       0  1  2  3  4  5  6  7  8  9  A  B  C  D  E  F
0000 .@@......U.silic E1 40 40 00 03 17 D1 01 13 55 04 73 69 6C 69 63
0010 onchip.com.au... 6F 6E 63 68 69 70 2E 63 6F 6D 2E 61 75 FE FF FF
0020 ................ 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
.
.
.
0130 ................ 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
```

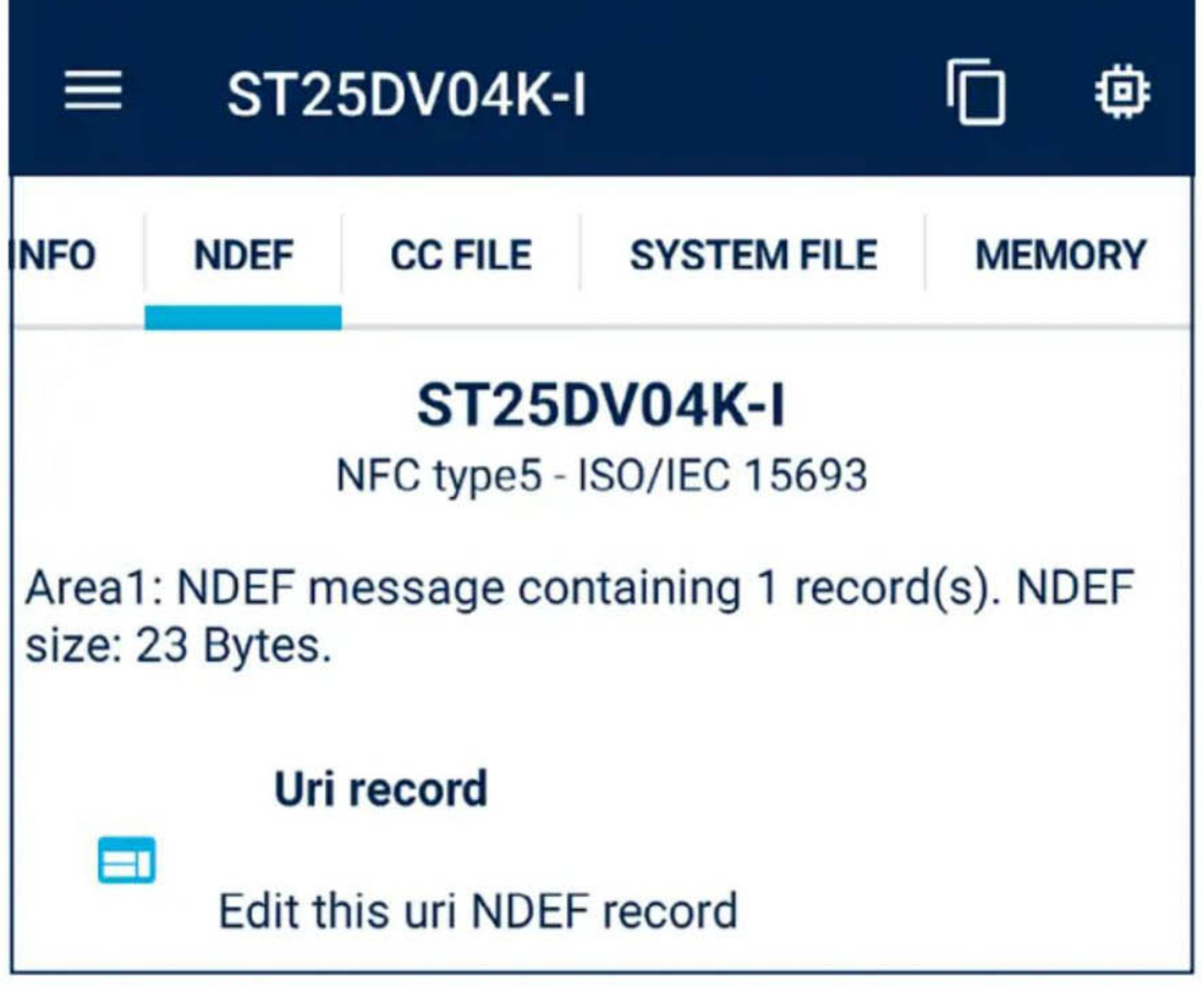
Screen 4: a raw dump of the tag chip's EEPROM can be handy for exploring the layout of the NDEF card structure. You can make out the URI content as raw text.

Parts List – Dynamic NFC Tag

1 22 × 31mm double-sided PCB coded 06101231 ***OR***
1 86 × 54mm double-sided PCB coded 06101232 from the *PE PCB Service*
1 ST25DV04K dynamic NFC tag chip, SOIC-8 (IC1) •
2 4.7kΩ ⅛W M3216/1206 SMD resistor
1 100nF 50V X7R M3216/1206 ceramic 'chip' capacitor

Programming jig parts

1 Raspberry Pi Pico (or Pico W) microcontroller board programmed with 0610123A.UF2
1 4-way male pin header, 2.54mm pitch
• *there are other options, listed in the introduction of the article*



Area1: NDEF message containing 1 record(s). NDEF size: 23 Bytes.

Screen 5: the tabs on the ST25 NFC Tap app allow you to view and edit the tags and their NDEF contents. This app might be all you need to program tags.

We often use the HxD hex editor on Windows to view files in hexadecimal format. This program also allows the hexadecimal data to be copied and pasted directly into the 'wb' command. However, you should be careful only to paste small amounts of data at a time so that the terminal and Pico can keep up with processing the data.

After entering the data, confirm the write and see that the data is written correctly. At this stage, the Tag should register if held near an NFC reader such as a smartphone. Most phones should process URIs, Wi-Fi handover records and vCard files without needing extra apps.

If you have trouble, ensure your mobile phone has NFC (not all do!), and it is turned on in the settings. Most newer phones should allow you to search your settings; typing 'nfc' should be sufficient to find the right one.

If you wish to lock the Tag so that it cannot be edited by someone accessing it via its RF interface, use the 'o' command to open a security session. There is a default password consisting of eight zero bytes, which is assumed to be unchanged. Finally, use the 'l3' command to set the write permissions to 'never allow RF to write'.

This won't change the I^2C permissions, so you can continue to edit the Tag content without unlocking the Tag for RF writes. Unlocking for RF writes is done with the 'l0' command.

Apps

We'll look at a couple of Android apps to read and write to these Tags. At the time of writing, it appears that there are iOS versions of these apps, which we expect to be fairly similar, although we haven't tried them.

The first is ST Microelectronics' 'ST25 NFC Tap' app, which is clearly targeted to work with this range of chips. You should, of course, ensure that your mobile phone supports NFC and that it is turned on.

Table 1 – commands for the programming jig

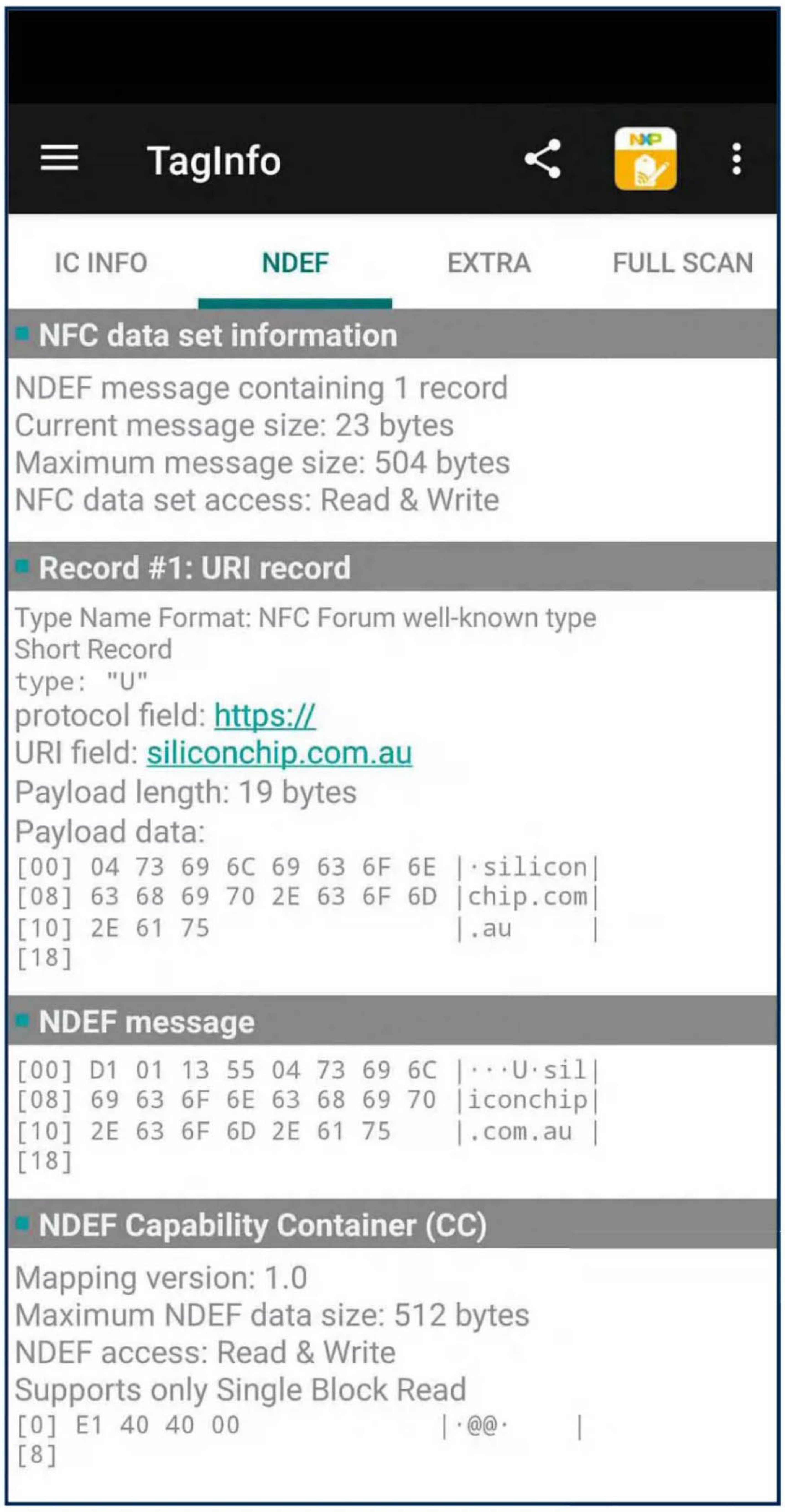
CMD	Function	*Notes*
	Reprint menu	*Simply press Enter on a blank line.*
~	Reboot Pico	*Use to refresh after connecting a Tag.*
r	Read NDEF messages from EEPROM; use 1-4 for a specific record (eg, 'r1')	*Uses the SparkFun library to decode NDEF data.*
a	Decode NDEF messages from EEPROM. Use 1-4 for a specific record (eg, 'a1')	*Uses custom code to perform a more detailed analysis than the 'r' command.*
c	Decode capability container and NDEF messages	*Uses custom code and provides more detail of the structure of the NDEF data rather than contents.*
i	Read UID data and check memory capacity	*The part number is printed if a known chip type is identified (including the supported chips).*
e	Erase EEPROM (to zeroes) and write a blank capability container	*Use this on a new chip to format it and allow NDEF records to be written. You can also use this to remove any previous data when reusing a Tag.*
wt	Write an NDEF text record to the Tag	*Prompts for text that can include line endings. Use Ctrl-D or Ctrl-Z to finish or Ctrl-C or Escape to cancel.*
ww	Write a Wi-Fi handover record to the Tag	*Prompts for SSID (name), password and security and encryption types.*
wu	Write a URI NDEF record to the Tag	*Prompts for URI type (eg, 'http:', 'mailto:') and URI text. The URI type simply allows common types to be easily abbreviated and can be omitted by using URI type zero (blank).*
wv	Write a vCard NDEF record to the Tag	*Creates a version 2.0 vCard file and prompts for all mandatory fields for that format. Also prompts for custom fields.*
wm	Write text MIME type to the Tag	*Uses the same scheme as 'wt' but allows the MIME type to be specified. Most mobile phones will treat 'text/plain' types the same as an NDEF text type record, if they have an app that supports that type.*
wb	Write binary MIME type to the Tag	*Prompts for MIME type and accepts hex bytes (or single nibbles if separated by white space). Use Ctrl-D or Ctrl-Z to finish or Ctrl-C or Escape to cancel.*
d	Dump ASCII and text contents of the Tag's EEPROM	*This is handy for viewing the raw EEPROM contents if you want to see how the NDEF entries are encoded and decoded.*
h	Write a single byte to EEPROM	*The format is 'haaaadd' where aaaa is a 16-bit address and dd is 8-bit data in hexadecimal format.*
o	Opens a security session using the default '00000000' password	*This is needed to permit command 'l' to work.*
s	Dump system memory and dynamic registers	*You would only use this if you were interested in the advanced features of the chip.*
l	Modify the RF lock bits	*'l0' clears the lock bits and allows RF writes to EEPROM. 'l3' forbids RF writes to EEPROM, so the contents can only be modified via I^2C.*

This app allows you to do many of the things that the Arduino Programming Rig can do, although we found it occasionally crashed if the card was moved while reading or writing.

Screen 1 shows a typical overview. The NDEF and CC FILE tabs allow the NDEF data to be viewed and edited, while the MEMORY tab allows the EEPROM to be directly viewed (similar to using the 'd' command in the Programming Rig).

Screen 5 shows the NDEF tab. You can use the button at bottom right (cut off in the screen grab shown) to create a new NDEF record, while one of the buttons at top right allows NDEF records to be cloned. If you haven't built the Arduino programming rig, cloning is probably the easiest way to create multiple identical Tags.

This app can add multiple NDEF records to a single Tag; Screen 6 shows some of the record types that can be added. SMS and email records are specific types of URI records.


TagInfo

IC INFO | NDEF | EXTRA | FULL SCAN

NFC data set information

NDEF message containing 1 record
Current message size: 23 bytes
Maximum message size: 504 bytes
NFC data set access: Read & Write

Record #1: URI record

Type Name Format: NFC Forum well-known type
Short Record
type: "U"
protocol field: https://
URI field: siliconchip.com.au
Payload length: 19 bytes
Payload data:

```
[00] 04 73 69 6C 69 63 6F 6E |·silicon|
[08] 63 68 69 70 2E 63 6F 6D |chip.com|
[10] 2E 61 75                |.au     |
[18]
```

NDEF message

```
[00] D1 01 13 55 04 73 69 6C |···U·sil|
[08] 69 63 6F 6E 63 68 69 70 |iconchip|
[10] 2E 63 6F 6D 2E 61 75    |.com.au |
[18]
```

NDEF Capability Container (CC)

Mapping version: 1.0
Maximum NDEF data size: 512 bytes
NDEF access: Read & Write
Supports only Single Block Read

```
[0] E1 40 40 00             |·@@·    |
[8]
```

Screen 7: the NXP TagInfo app can read tags and also decode NDEF messages and records. There is also an NXP TagWriter app that we have not tried. It could possibly be used to customise Tags too.

An SMS record has the format 'sms:(phone number)?body=(message text)', with the bracketed items replaced by the phone number and message text (without brackets), respectively. You could also use the Arduino Programming Rig to create such a record as a URI type.

An email record has a similar format, using the 'mailto:' URI type (type 6) followed by an email address. It can optionally have a '?subject=...' field as well as body text ('&body=...').

Most mobile phones that we tested were able to handle all those records.

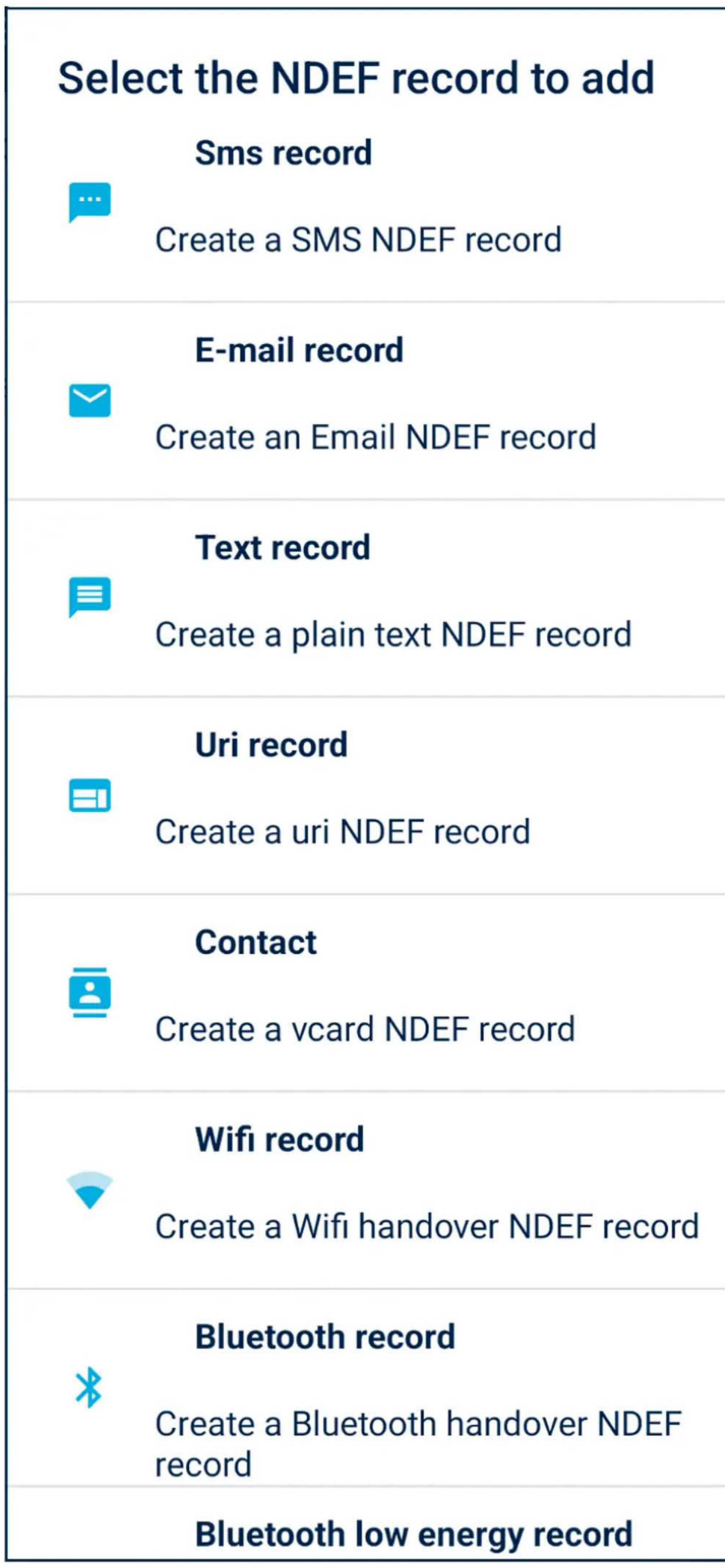
We're familiar with the NXP TagInfo app, as this can also read ISO14443A cards, such as those that can be read by PN532-based modules. Screen 7 shows a scan of a Tag containing a URI NDEF record using the TagInfo app.

Since it can read and interpret NDEF messages, this can be used to validate that Tags have been written correctly by either the Arduino Programming Rig or the ST25 app.

Conclusion

NFC tags are common these days, and we think many readers will relish the opportunity to create their own smart business cards and custom Tags.

We are investigating other ways to use these Tags. One idea is to use them to configure projects wirelessly without needing screens, displays or buttons to be built into the project. That could save quite a bit of time and money.


Select the NDEF record to add

Sms record
Create a SMS NDEF record

E-mail record
Create an Email NDEF record

Text record
Create a plain text NDEF record

Uri record
Create a uri NDEF record

Contact
Create a vcard NDEF record

Wifi record
Create a Wifi handover NDEF record

Bluetooth record
Create a Bluetooth handover NDEF record

Bluetooth low energy record

Screen 6: the ST25 NFC Tap app can create various NDEF record types, as shown here. There is also a tab allowing the EEPROM to be directly edited.

In such a project, the Tag circuit described here becomes part of the project, with IC1 accessed over an I^{2}C bus. The project can read (or write) its configuration to a text NDEF record on the Tag, which a suitably equipped smartphone or tablet can then view or edit.

There are undoubtedly other excellent applications for these Dynamic Tags, and we look forward to thinking of new ways to use them in future projects.

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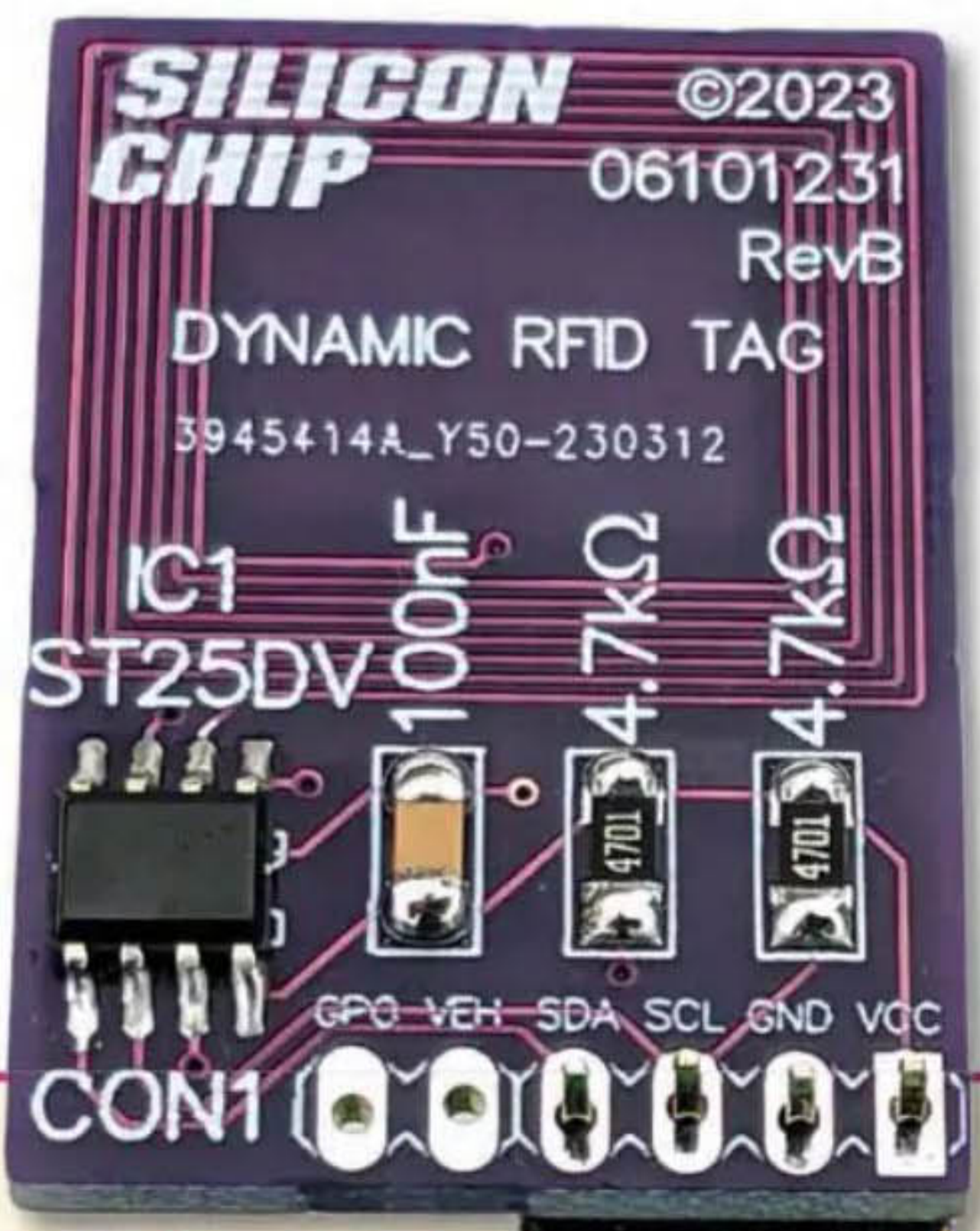
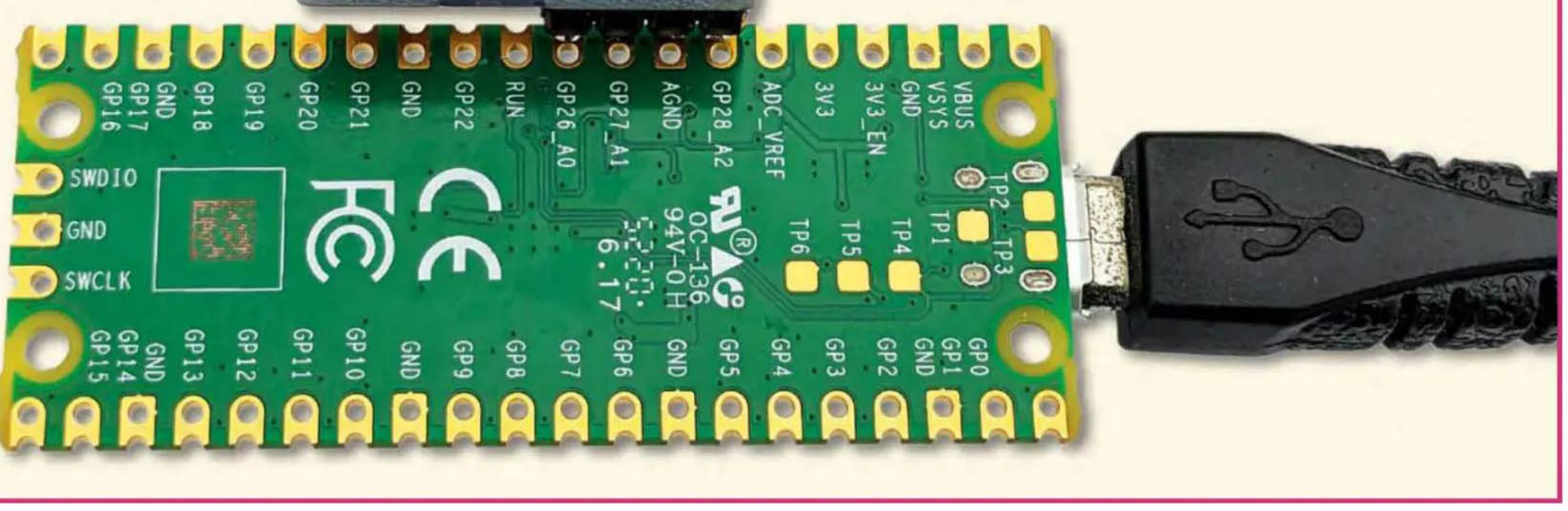
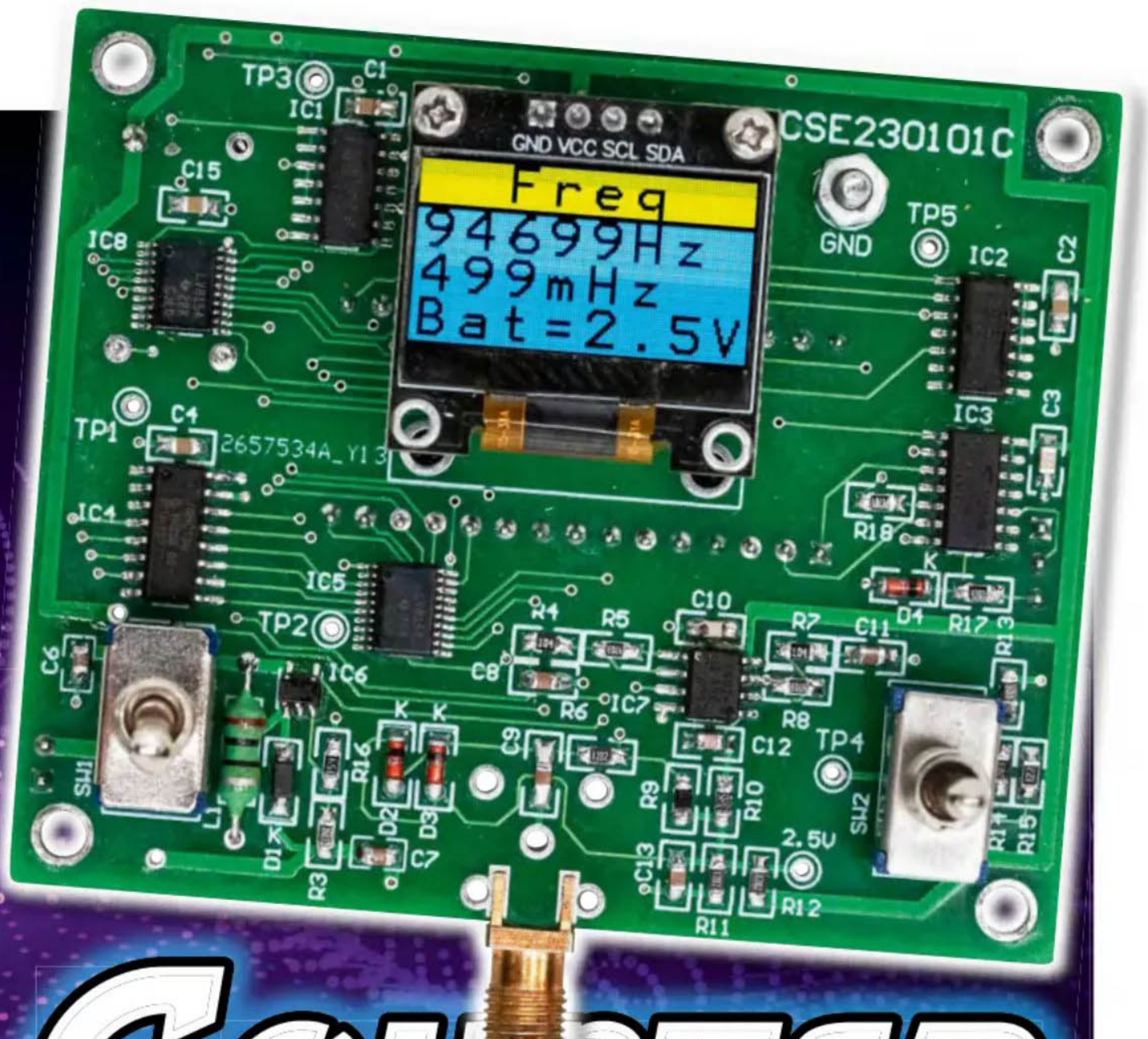



GP16 GND GP17 GP18 GP19 GP20 GP21 GND GP22 RUN GP26_A0 GP27_A1 AGND GP28_A2 ADC_VREF 3V3 3V3_EN GND VSYS VBUS
SWDIO
GND
SWCLK
GP15 GP14 GND GP13 GP12 GP11 GP10 GND GP9 GP8 GP7 GP6 GND GP5 GP4 GP3 GP2 GND GP1 GP0

We soldered a four-way header to the GP26, GP27, AGND and GP28 pins of the Pico. The holes in the Tag PCBs are staggered slightly to make good enough contact for programming without soldering. Check that the orientation and pin connections are correct, so you don't destroy the chip or the Pico.

Project by Charles Kosina

This design measures low-frequency signals accurately and quickly. A traditional frequency counter must sample over a long period to get an accurate result. This one instead measures the average period and calculates the inverse, so it only needs to monitor a few pulses to get a precise reading. It's useful up to about 10MHz.



Reciprocal Frequency Counter

I bought a frequency counter over 30 years ago, but its accuracy is very poor by today's standards, being out by as much as 50Hz at 10MHz. I replaced its not-very-accurate clock module with a 10MHz TCXO, and I can now rely on it to be within 1Hz at 10MHz. By adjusting the TCXO frequency to match that of my GPS-disciplined 10MHz frequency standard, I can be assured of such accuracy.

But what happens when I want to measure low frequencies? For example, a 50Hz signal. With a gate time of one second, it will most likely show a reading of 50, even if it is not exactly that. It might flip to 49 or 51, but the resolution is only 1Hz.

To improve that, we could have a gate time of 10 seconds and a resolution of 0.1Hz. For a 10mHz resolution, a 100-second gate time would be required, which is quite ridiculous.

A better way to measure low frequencies is to measure the period. With the same example of 50Hz, using a 10MHz clock, it would accumulate 200,000 pulses in one 20ms period. If the number of pulses measured were actually 199,900, that would mean that the frequency is 10,000,000 ÷ 199,900 = 50.025Hz.

That's a great improvement in resolution, but highly dependent on the accuracy of the hardware in measuring precisely one cycle. Also, as the signal frequency increases, the resolution and accuracy decrease.

One good thing about this scheme is that the exact measurement time is not critical, as the frequency calculation is ratiometric. This means that we should get reasonably accurate results as long as we have a clock source with an accurate frequency and synchronise the measurement period to the rising edges of the input signal pulse train.

What do we need to measure with such precision? Mains frequency was the first thing I tried. I connected the output of a 6V AC mains transformer to an RC network to reduce the voltage and filter out noise.

The frequency did vary slightly from reading to reading, and the largest variation was about 30mHz. This is within the required Australian Energy Market Operator (AEMO) specification of 49.85-50.15Hz. The frequency variation is caused by constantly changing load conditions on the network.

Also, musical instruments need to be tuned to very precise frequencies. In the equal-tempered scale, C4 (middle C) should be 261.63Hz. Concert pitch A4 must be 440.00Hz. All other notes require the same precision, to two decimal places, and a trained ear can pick the slightest differences in pitch. Such frequencies could be measured accurately and quickly using a microphone amplifier and this device.

Features and Specifications

- ► Operating frequency range: 10mHz-10MHz (maximum ~13.5MHz)
- ► Input sensitivity: 100mV peak-to-peak (~35mV RMS for a sinewave)
- ► Accuracy: typical error <0.001Hz up to 9.999MHz after calibration
- ► Sampling time: 0.1s, 1s or 5s
- ► Reference oscillator: temperature-compensated crystal oscillator (TCXO)
- ► Power: three AA cells for about 24 hours of battery life

Functional description

Refer to the timing diagram, Fig.1, which is not to scale. The input signal is fed into the clock input of a D-type flip flop (74HC74). While the D input (GATE TIME) remains low, the Q output remains low, and the counters are inhibited. We start the counting period by applying a logic one (high level) to the D input. On the next rising edge of the input signal, the Q output (COUNTEN) will go high after the short propagation delay.

Two NAND gates are turned on as a result. The reference clock (REF COUNT) is then applied to 32-bit counter IC5, and the input signal, INPUT COUNT, is applied to the other 32-bit counter, IC8.

After one second, the D input of the 74HC74 is taken low. The Q output remains high until the next positive edge of the input signal, when it will go low. This stops the accumulation of counts in both the 32-bit counters. Importantly, we have an exact input count as the period is synchronised with the rising edges of the input signal.

The reference counter is not synchronised the same way, so the count could be out by one. With a 10MHz reference oscillator, this results in an error of one part in 10^7. But, with a 30MHz reference, it reduces to 0.33 parts in 10^7, which is insignificant.

We now have three parameters. The reference clock is a TCXO and so it is very accurate. IC5 will contain a number accumulated over the (approximate) one-second period, and this is the Reference Count, which will be near the Reference Oscillator frequency. The other counter, IC8, has

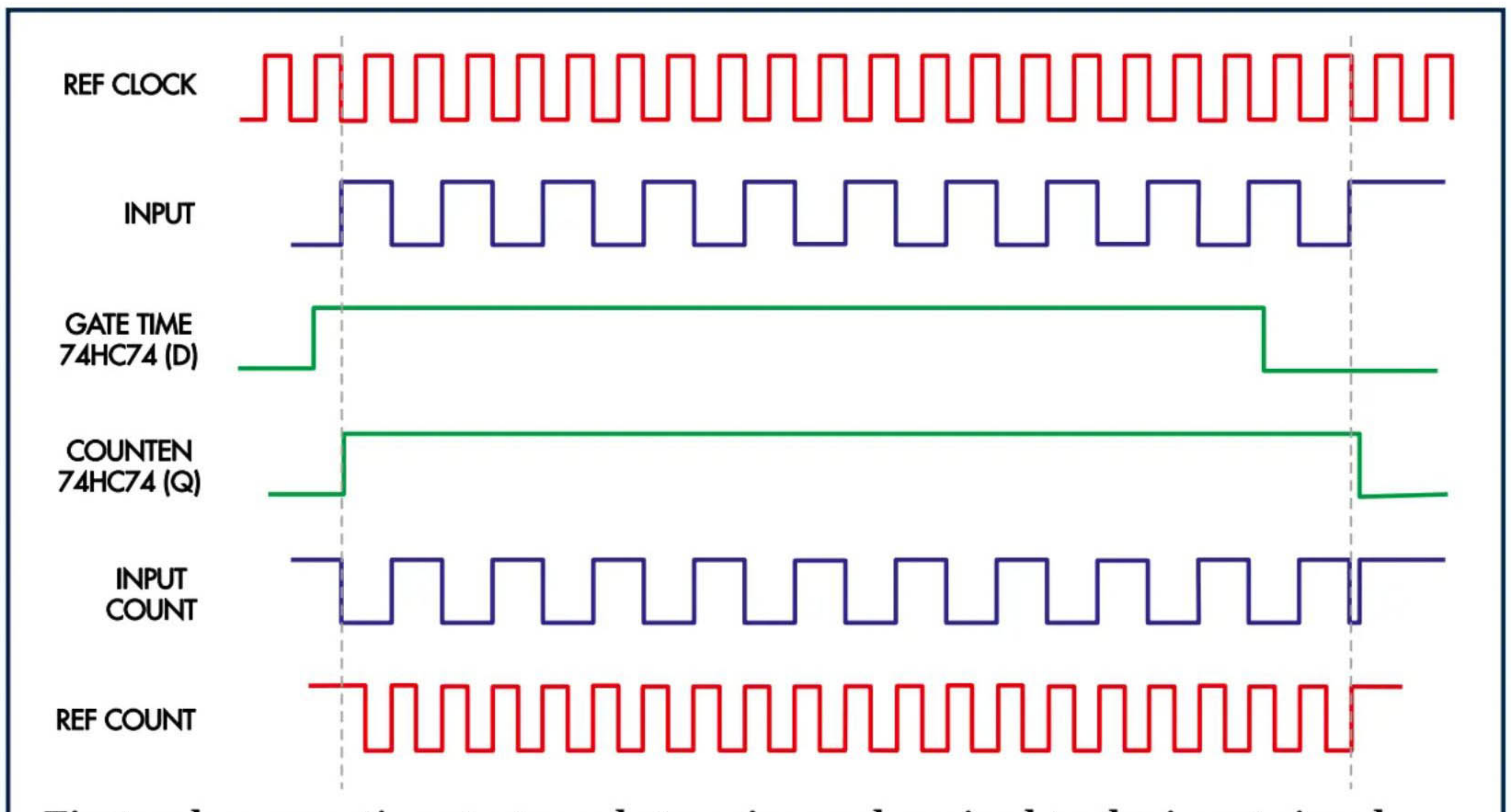


Fig.1: when counting starts and stops is synchronised to the input signal. GATE TIME indicates roughly when counting should occur. However, the synchronised COUNTEN signal actually starts and stops counting (of INPUT COUNT and REF COUNT). The two count values are then divided to get a ratio and thus determine the actual input signal period.

the Input Count. The frequency is then calculated from the equation:

f = Input Count × Ref Osc ÷ Ref Count

Circuit description

Fig.2 shows the full circuit of the Counter. The input signal from CON2, a BNC or SMA connector, is amplified by the Analog Devices ADA4891-2 dual op amp, IC7. With the values shown, the gain is about 32, but that could be increased by changing a couple of resistors. A minimum input signal of 50-100mV peak to peak is needed.

I chose that op amp as it has a high input impedance, a gain bandwidth (GBW) of 220MHz and a respectable slew rate of 170V/µs. It is also readily available from multiple suppliers at a modest price. The gain is applied in two stages of about five times each, to keep the overall bandwidth high.

Inverse parallel diodes D2 and D3 limit the input level to the first op amp and prevent overload. The output of the second op amp (IC7b) is squared up by a 74HC14 schmitt trigger inverter (IC3a). Its output feeds into the clock input of 74HC74 flip-flop IC2a that produces the COUNTEN flag at its Q1 output, as well as a 74HC10 NAND gate (IC1c) producing the $\overline{\text{COUNT}}$ signal.

I am using two 74HC10 three-input NAND gates with two of their inputs tied together instead of the two-input 74HC00 purely because of what I had in stock. I only need two of these gates, so using a 74HC00 with four gates wouldn't be more helpful.

The $\overline{\text{COUNT}}$ signal goes to both clock inputs of a 74LV8154 32-bit counter, IC8. A second such counter, IC5, is driven by the TCXO output, also gated by the COUNTEN signal, thanks to NAND gate IC1a, as described earlier.

The microcontroller can clear both counters using the $\overline{\text{CCLR}}$ signal before initiating a count. That same signal also resets flip-flop IC2a, de-asserting the COUNTEN signal. Once counting is finished, the microcontroller can read the values from both 32-bit counters using an 8-bit data bus (CNTR0-7), selecting one byte from one 32-bit counter at a time (for a total of eight).

Which byte is read out depends on the states of the $\overline{\text{SIG COUNT}}$ and $\overline{\text{30MHZ\_COUNT}}$ lines, which select one counter, and the SEL0/SEL1 bits, which select which byte of that counter is on the 8-bit bus, controlled by both halves of the 74HC139 dual 2-to-4 line decoder, IC4.

The processor used is an Arduino Nano microcontroller module with an onboard ATmega328 microcontroller. These are available from many sources and are cheaper than buying the separate individual components, plus it removes some of the hard work in assembly.

The display is the same 0.96-inch monochrome graphical OLED I have used in several previous designs. The Nano updates its display over a two-wire I^2C serial interface with two 4.7kΩ pull-up resistors as required by the I^2C standard.

Switch S2 provides three sample time options: 0.1s, 1s or 5s. One second is adequate for most measurements. The five-second option may give marginally better resolution and accuracy. The 0.1 second gives a fast approximate reading.

The microcontroller reads the position of centre-off switch S2 using its analogue-to-digital converter to measure the voltage at pin 11 (ADC7). The switch either presents 0V, half-supply (2.5V) or close to full supply (5V).

The power supply for basically all the chips in the design is a regulated 5V from boost regulator REG6. It produces this 5V from the 3-4.5V generated by three series AA cells, and its input is switched on/off by switch S1.

CON3 and three more of the inverters in IC3 provide a serial debug interface. Unless you plan to modify the code, it isn't that useful, so CON3 and D4 can usually be left off the board.

Software calculations

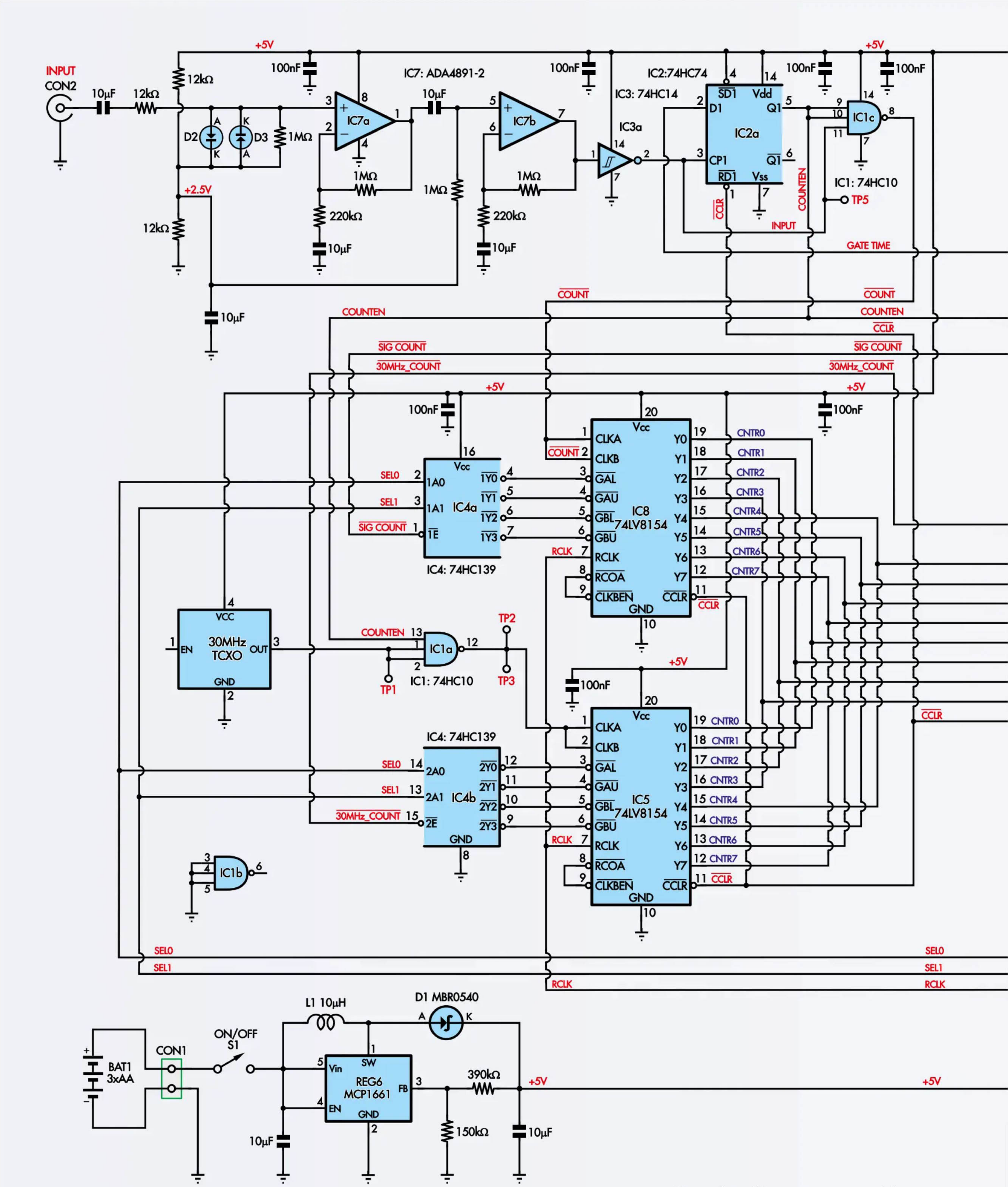
The formula above certainly is simple, with just one multiplication and one division, but the numbers involved are large. We need to multiply before

RECIPROCAL FREQUENCY COUNTER
ON
1 SEC
1 SEC
5 SEC

The Counter is battery-powered, making it convenient to use.

dividing so that we don't lose accuracy, meaning we need to calculate an intermediate value that can be as high as 3,000,000,000,000 (three trillion; with a 10MHz input and 30MHz oscillator).

That is way beyond 32-bit integer arithmetic. I use the BASCOM compiler, which can perform double-precision floating-point calculations using 64 bits. That's enough to store numbers that large without any accuracy loss. For an 8-bit processor running at 16MHz, the above calculation takes 0.4ms, which is quite impressive for such an inexpensive chip.


INPUT
CON2
10µF
12kΩ
+5V
12kΩ
100nF
D2
D3
1MΩ
+2.5V
12kΩ
10µF
IC7a
IC7: ADA4891-2
1MΩ
220kΩ
10µF
1MΩ
IC7b
1MΩ
220kΩ
10µF
100nF
IC3: 74HC14
IC3a
IC2:74HC74
IC2a
SD1
Vdd
D1
Q1
CP1
Q1
RD1
Vss
100nF
100nF
IC1c
IC1: 74HC10
TP5
CCLR
INPUT
COUNTEN
GATE TIME
COUNT
COUNTEN
CCLR
SIG COUNT
30MHz_COUNT
100nF
100nF
IC8
74LV8154
CLKA
CLKB
GAL
GAU
GBL
GBU
RCLK
RCOA
CLKBEN
Vcc
GND
Y0
Y1
Y2
Y3
Y4
Y5
Y6
Y7
CCLR
CNTR0
CNTR1
CNTR2
CNTR3
CNTR4
CNTR5
CNTR6
CNTR7
IC4a
IC4: 74HC139
SEL0
SEL1
SIG COUNT
1A0
1A1
1E
1Y0
1Y1
1Y2
1Y3
30MHz TCXO
VCC
EN
OUT
GND
COUNTEN
IC1a
IC1: 74HC10
TP1
TP2
TP3
IC4: 74HC139
IC4b
2A0
2A1
2E
2Y0
2Y1
2Y2
2Y3
30MHz_COUNT
IC5
74LV8154
IC1b
SEL0
SEL1
RCLK
BAT1
3xAA
CON1
ON/OFF
S1
L1 10µH
D1 MBR0540
REG6
MCP1661
Vin
SW
EN
FB
GND
390kΩ
150kΩ
10µF
10µF
+5V

Reciprocal Frequency Counter

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The oscillator

TCXOs are readily available from AliExpress for about £8-10. I tried four different frequencies: 10MHz, 25MHz, 30MHz and 40MHz. The only change needed in the BASCOM source code was the substitution of one number.

The higher frequencies give the advantage of slightly better resolution and accuracy. 40MHz is the maximum that can be used with the 74LV8154 counters, but it appears to be pushing the limit, as the accuracy seemed to drop off. So 30MHz is the best option.

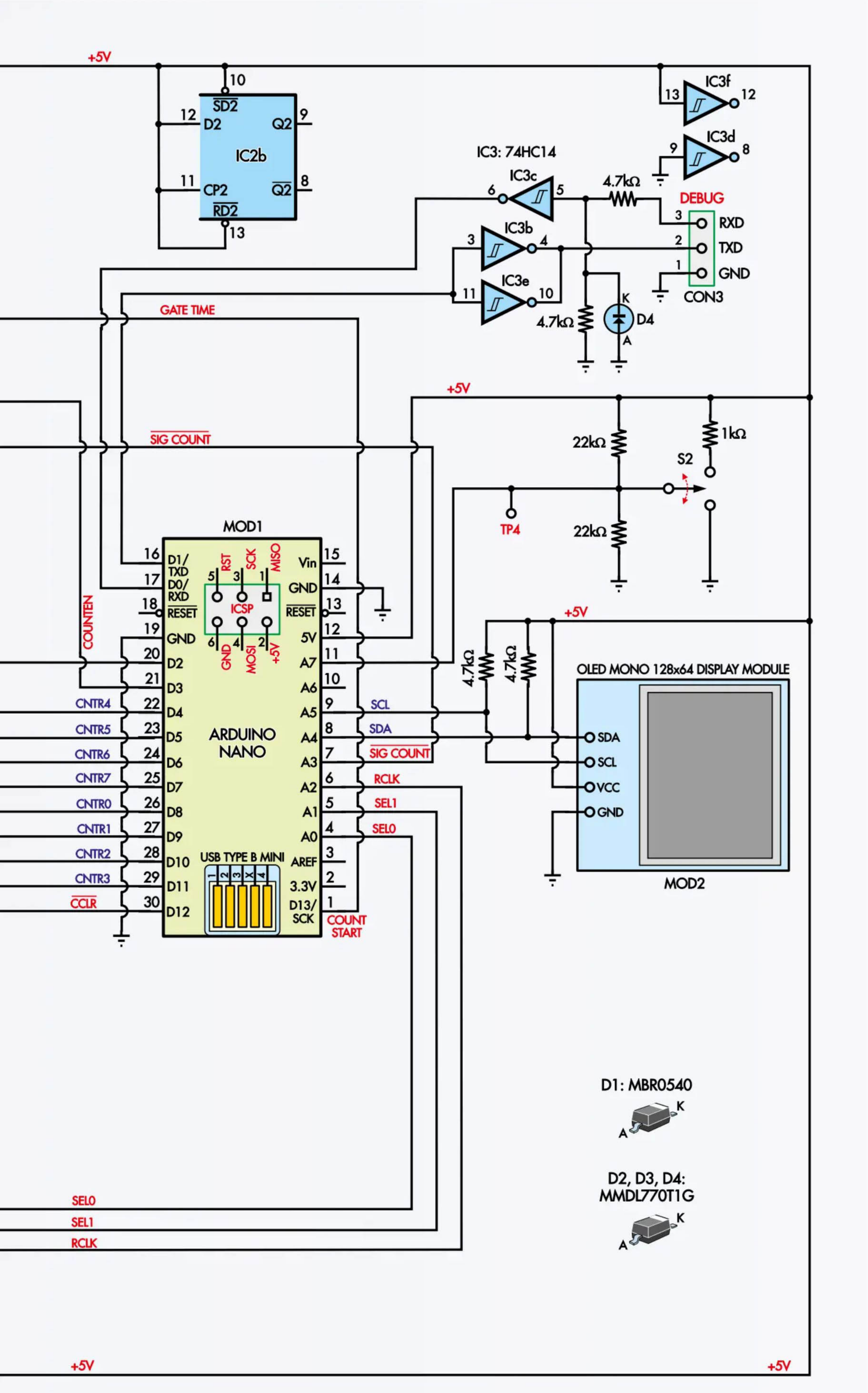

+5V
IC2b
SD2
D2
Q2
CP2
Q2
RD2
10
12
9
11
8
13
IC3f
13
12
IC3d
9
8
IC3: 74HC14
IC3c
6
5
4.7kΩ
DEBUG
IC3b
3
4
3
RXD
2
TXD
1
GND
CON3
IC3e
11
10
K
4.7kΩ
D4
A
GATE TIME
+5V
SIG COUNT
22kΩ
1kΩ
S2
TP4
22kΩ
MOD1
16
D1/TXD
17
D0/RXD
18
RESET
19
GND
20
D2
21
D3
22
D4
23
D5
24
D6
25
D7
26
D8
27
D9
28
D10
29
D11
30
D12
RST
SCK
MISO
5
3
1
ICSP
6
4
2
GND
MOSI
+5V
Vin
15
GND
14
RESET
13
5V
12
A7
11
A6
10
A5
9
A4
8
A3
7
A2
6
A1
5
A0
4
AREF
3
3.3V
2
D13/SCK
1
ARDUINO NANO
USB TYPE B MINI
1
2
3
X
4
COUNTEN
CNTR4
CNTR5
CNTR6
CNTR7
CNTR0
CNTR1
CNTR2
CNTR3
CCLR
SCL
SDA
SIG COUNT
RCLK
SEL1
SEL0
COUNT START
+5V
4.7kΩ
4.7kΩ
OLED MONO 128x64 DISPLAY MODULE
SDA
SCL
VCC
GND
MOD2
D1: MBR0540
K
A
D2, D3, D4: MMDL770T1G
K
A
SEL0
SEL1
RCLK
+5V
+5V

Fig.2: the entire Frequency Counter circuit. Signal conditioning is at upper left; the counters are left of centre, the power supply is at lower left and the microcontroller and display are on the right. The micro decides when to start and stop counting and when to reset the counters. It is responsible for reading the counter values, computing the frequency and displaying it on the OLED screen.

It would be nice to have the frequency readout in one row of large digits. But in keeping with the style of my previous designs, I have used the same small OLED to show four lines of eight characters per line. That is not enough to display the frequency on one line, so it is split into two lines.

The top line shows 'FREQ' while the second line display up to 9,999,999 (Hz). The third line shows the remainder in mHz, from 0 to 999, while the final line displays the battery voltage.

Accuracy

The primary factor that affects accuracy is how close the TCXO is to its stated frequency. The second factor is the precision of the mathematical calculations, but with the use of 64-bit floating point arithmetic, any errors are minimal.

I used my 10MHz GPS-disciplined oscillator as an input to a 14-bit counter (74HC4060) and fed ten different divided frequencies into the *Reciprocal Frequency Counter*. Table 1 shows the results with the 30MHz TCXO straight out of the box with no adjustment.

I then tuned the 25MHz TCXO to within less than 1Hz, and the errors were 1mHz or less for all of the frequencies shown in Table 1.

The TCXOs I bought from AliExpress suppliers have been very close to the stated frequency, but it is possible to adjust them by peeling the label off the TCXO, which gives access to a trim capacitor. However, this is not for the faint-hearted, as it is an extremely fine adjustment, and unless you have the equipment and patience, I don't recommend it.

You need a dual-trace oscilloscope with one channel connected and locked to a GPS-disciplined 10MHz oscillator and the other to the TCXO output. The latter will drift left or right, and the trimmer should be adjusted for minimum drift. If it takes five seconds to drift one cycle, that's an error of 0.2Hz (1Hz ÷ 5).

Frequency limits

The maximum frequency of this counter is partially limited by the op amp used in the input amplifier. The ADA4891 has a gain bandwidth (GBW) of 220MHz and a slew rate of 170V/µs (it was also chosen for its high input impedance and GBW). This limits the maximum usable frequency to about 15MHz; however, readings above 10MHz tend to become rather erratic.

Table 1 – readings from high-precision source without calibration

Division ratio	Input signal	Measurement	Error
÷16384	610.3515625Hz	610.352Hz	1mHz
÷8192	1,220.703125Hz	1220.703Hz	<1mHz
÷4096	2,441.40625Hz	2441.406Hz	<1mHz
÷1024	9,765.625Hz	9765.625Hz	<1mHz
÷512	19,531.25Hz	19,531.249Hz	1mHz
÷256	39,062.5Hz	39,062.500Hz	<1mHz
÷128	78,125.0Hz	78,124.998Hz	2mHz
÷64	156,250.0Hz	156,249.995Hz	2mHz
÷32	312,500.0Hz	312,499.990Hz	10mHz
÷16	625,000.0Hz	624,999.980Hz	20mHz

Table 2 – high-frequency measurements

Input frequency	Measurement	Error
1MHz	999,999.990Hz	10mHz
2MHz	1,999,999.870Hz	130mHz
5MHz	4,999,999.670Hz	330mHz
8MHz	7,999,999.530Hz	470mHz
10MHz	9,999,999.330Hz	670mHz

I used my calibrated AD9851 signal generator to check frequencies above 1MHz; the results are shown in Table 2.

The higher error rates above 1MHz appeared to be due to the TCXO being slightly off from its nominal 30MHz frequency.

The lower end of the frequency limit is determined by the input components (10µF/1MΩ) which gives a -3dB point of 16mHz. Therefore, the practical lower limit is about 10mHz. Measuring a 0.1Hz signal would take around 10-20 seconds, but that is the nature of low-frequency signals.

Construction

The assembled PCB is designed to fit into the Altronics H0324 plastic enclosure with a clear lid, so we don't need to cut a hole for the display. Before mounting any components on the PCB, use it as a template to drill holes into the clear lid. The PCB just fits in the front detent. Attach it with sticky tape and drill the four corner mounting holes with a 3mm drill. Use a 1.5-2.0mm drill for the two switch centre holes.

Remove the PCB, drill out the switch holes to 6mm and countersink the mounting holes for M3 countersunk head screws (in this case, 6mm long).

The triple AA battery holder should be attached to holes in the bottom of the enclosure using self-tapping countersunk head screws of around 3mm in diameter (4G in the old scheme).

Next, move on to building up the PCB, which is coded CSE230101C, measures 76 × 63.5mm, and is available from the *PE PCB Service*. During construction, refer to the PCB overlay diagram, Fig.3. Most of the components on it are surface-mount devices (SMDs). The two 32-bit counters, IC5 and IC8, come in relatively fine-pitch 20-pin TSSOP packages, so solder them first.

The first and most important job is to identify pin 1 and ensure it is positioned correctly; you don't want to finish soldering an IC to realise it's the wrong way round! There should be a dot, or similar marking, in the pin 1 corner but you might need a magnifier to see it.

Working one at a time, carefully position the chip on the pads and solder opposite corners without worrying about shorting pins. You need to ensure the pins are accurately aligned over the pads on both sides, though, so tack one corner first and only solder the other once the alignment looks good under a magnifier.

Next, spread flux down both sides and slowly drag the soldering iron tip along the pins. You might finish up with a blob of solder on the last couple of pins, so use a bit of extra flux paste and some solder braid (wick) to remove it. Use a loupe or similar to check that all the pins have been soldered properly and that there are no shorts between them. If there are, break out the flux and wick again.

It helps to clean off the flux residue using an appropriate solvent and then do a final inspection before moving on because the residue can hide mistakes.

With those nicely soldered, use a similar technique to solder the remaining

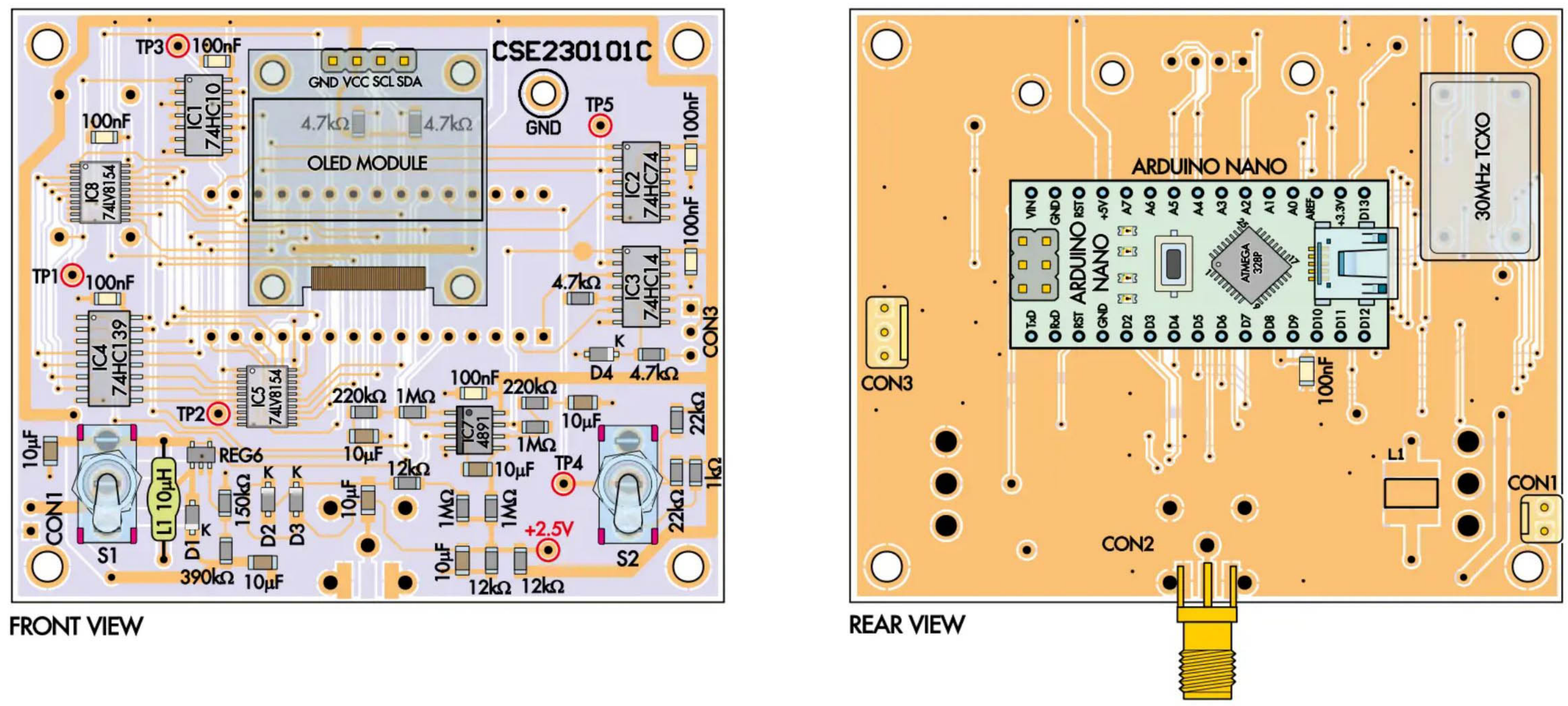


Fig.3: most parts are SMDs that mount on the top side of the board, but there are a handful of through-hole parts plus a few components on the back, notably the TCXO and Arduino Nano module. L1 can be either a through-hole type on the front or a 4 × 4mm SMD inductor on the back. Watch the polarity of all the ICs, the regulator and the diodes.

SMD ICs, which have larger lead pitches, so they should be easier. Don't get IC1, IC2 and IC3 mixed up; they all come in 14-pin SOIC/SOP packages.

Regulator REG6 has three pins on one side and two on the other, so its correct orientation should be obvious. Start by tacking one of the two pins on one side as they have better separation. Use a similar technique as for the ICs, noting that a single pass with solder wick should clear any bridges from the three-pin side.

Move onto the four diodes, noting that the different types come in different style packages, all rectangular prisms but with D2-D4 being smaller (there are various compatible types). In each case, ensure the cathode stripe is facing towards the nearest 'K' marking on the PCB (cathode is 'Kathode' in German).

After that, solder the SMD passives (capacitors and resistors) similarly. The resistors will be marked with codes indicating their values, while the capacitors will likely be unmarked, so don't mix them up once they are out of their packages. Still, the 10µF caps will probably be thicker than the 100nF types.

Moving onto inductor L1, there are two options. A moulded 10µH axial inductor may be used on the front side of the board, but a better choice is a 4 × 4mm SMD inductor on the other side of the board. The SMD option gives slightly higher boost converter efficiency and thus marginally longer battery life.

With most of the SMDs in place, mount the through-hole parts. The OLED plugs into a 4-pin socket strip and is attached by two M2 × 15mm screws and untapped spacers. Carefully slide off the plastic spreader on the pins of the OLED header to reduce its height, then cut 3mm off the pins using side cutters.

The OLEDs come in two slightly different sizes, and some are slightly shorter. If necessary, attach it using the holes on either side of the connector rather than the bottom pair.

The Arduino Nano mounts on the back of the board and plugs into socket strips. Don't solder it in directly, as you then can't get at the OLED screw holes! It's important to use low-profile pin sockets; otherwise, there is not enough room for the battery underneath.

Fit the other components on the reverse side next, ie, the connectors, TCXO and additional 100nF capacitor. The input connector is an edge-mounted SMA type. Ensure the TCXO is mounted with the correct orientation, having its pointy corner (indicating pin 1) towards the top of the board.

Parts List – Reciprocal Frequency Counter

1 125 × 85 × 55mm IP65 sealed ABS enclosure **[Altronics H0324]**
1 3 × AA battery holder (BAT1)
3 AA cells
1 double-sided PCB coded CSE230101C, 76 × 63.5mm
1 double-sided PCB coded CSE230102, 1mm thick with black solder mask, 76.5 × 63.5mm (front panel) both from the *PE PCB Service*
1 Arduino Nano module (MOD1)
2 15-pin headers (for MOD1)
2 15-pin low-profile female header strips (to plug MOD1 into)
1 0.96-inch 128×64 pixel I^2C OLED screen module (MOD2) **[SC6176]**
1 10µH axial RF inductor ***OR*** 4 × 4mm SMD inductor (L1) **[eg, NRS4018T100MDGJ]**
1 SPDT miniature solder-lug on/on (latching) toggle switch (S1)
1 SPDT miniature solder-lug on/off/on (latching centre-off) toggle switch (S2)
1 2-pin polarised header and matching plug (CON1)
1 SMA edge connector socket (CON2)
1 3-pin polarised header (CON3 for debugging; **optional**)
1 4-pin female header (for MOD2)
4 M3 × 6mm panhead machine screws
4 M3 × 6mm countersunk head machine screws
4 M3-tapped 12mm spacers
4 M3 flat washers
2 8mm-long untapped spacers (minimum 2mm inner diameter)
2 M2 × 16mm machine screws and nuts
2 3mm/4G x 6mm countersunk head self-tapping screws (for battery holder)

Semiconductors
1 74HC10 triple 3-input NAND gate, SOIC-14 (IC1)
1 74HC74 dual D-type flip-flop, SOIC-14 (IC2)
1 74HC14 hex schmitt trigger inverter, SOIC-14 (IC3)
1 74HC139 dual 2-to-4 line decoder, SOIC-16 (IC4)
2 SN74LV8154PW 32-bit counters, TSSOP-20 (IC5, IC8)
1 ADA4891-2ARZ dual high-bandwidth op amp, SOIC-8 (IC7)
1 MCP1661T-E/OT or MP1542DK-LF boost regulator, SOT-23-5 (REG6)
1 4-pin through-hole 30MHz TCXO, 20×13mm (OSC1) **[eg, www.aliexpress.com/item/32789207591.html]**
1 MBR0540 40V 500mA schottky diode, SOD-123 (D1)
3 MMDL770T1G 75V 200mA signal diodes, SOD-323 (D2-D4)

Capacitors *(all SMD M2012/0805 size)*
7 10µF 16V X7R
7 100nF 50V X7R

Resistors *(all SMD M2012/0805 size, 1%)*
4 1MΩ
1 390kΩ
2 220kΩ
1 150kΩ
2 22kΩ
3 12kΩ
4 4.7kΩ
1 1kΩ

The 3-pin header is only needed if you want to use the debugging interface.

While the switches have solder lugs, they are mounted on the PCB like through-hole components. Ensure they are perpendicular to the board surface and fully pushed down before soldering them. S2, the centre-off type, goes on the right side (from the front).

After you've cleaned the board, inspect it for missing or badly-formed joins and shorts between pins. You can then move on to programming the microcontroller.

Microcontroller programming

While we are using an Arduino Nano module with an onboard ATmega328 chip, we are not programming it with the Arduino IDE. The software is written in BASCOM and compiled into a HEX file. You can load that HEX file with an AVR ISP programmer, if you have one, via the 6-pin header on the Nano, but there is another method that doesn't require the programmer.

If you use the six-pin header for programming, there is a conflict with the I/O pins on the board, so it is necessary to unplug the Nano and connect it via the USB cable for power before flashing the chip. No fuses need to be changed; the defaults are fine, so it's ready once you've uploaded the HEX file.

Alternatively, plug the Nano into your computer using a USB cable. Then install and load a program like AVRDUDESS for Windows. You can use the AVRDUDE command-line program in Linux or macOS.

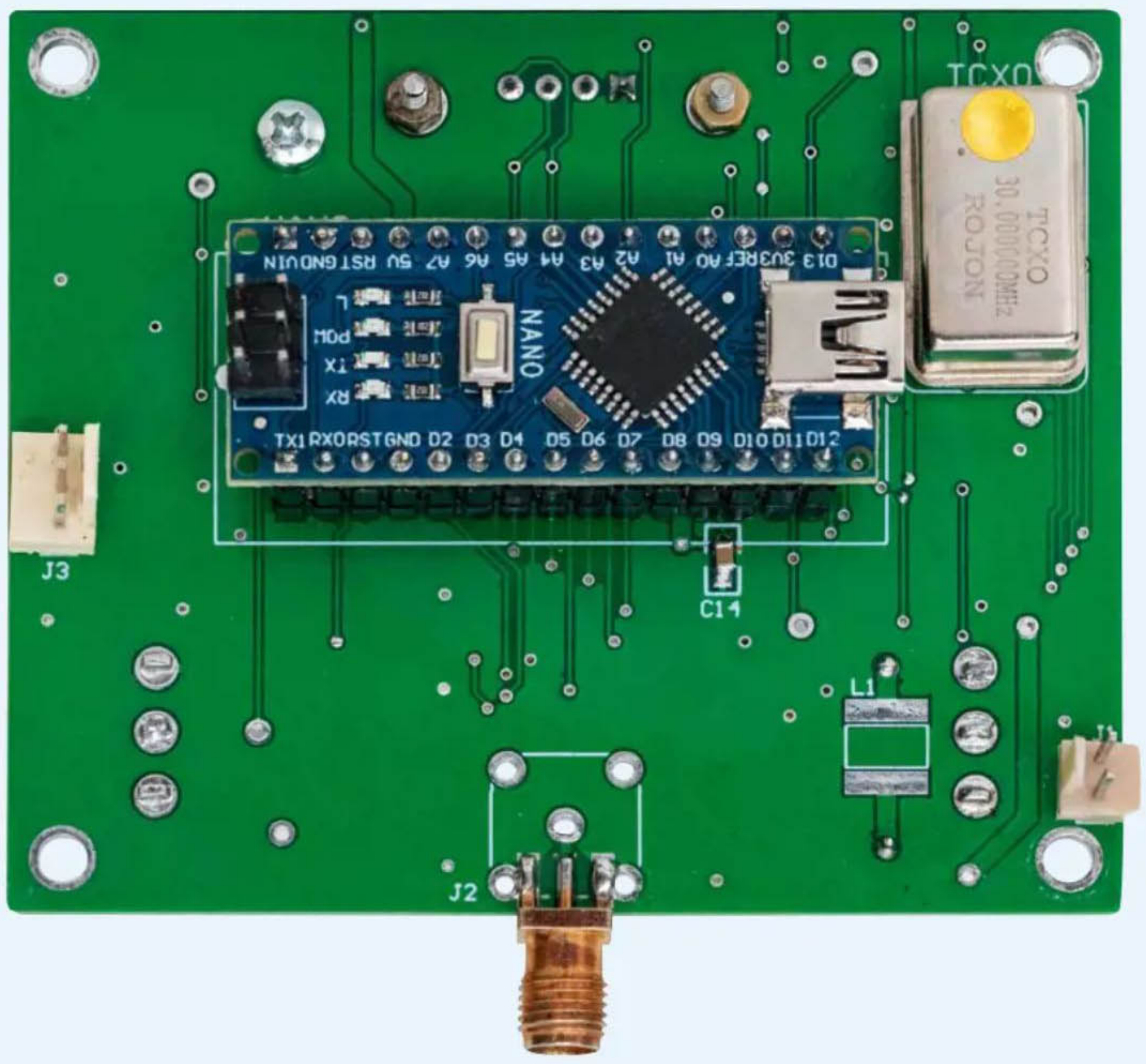
Set the programmer to Arduino, select the Nano's USB serial port, the baud rate to 115,200 or 57,600 (depending on your Nano) and click 'Detect'. If it doesn't find the chip, adjust the settings and try again. Once it does, go to the Flash window, open the HEX file for this project and click the program button. The file is available from the July 2024 page of the *PE* website: **https://bit.ly/pe-downloads**

Final assembly

Plug the Nano back into the PCB, and it can then be attached to the front panel (coded CSE230102) using 12mm spacers and M3 screws. Add a washer between the spacer and the front panel to increase the distance slightly. The front panel is another PCB, 1mm thick, with a black solder mask and white printing. It is held in place by the two switch nuts. Using a PCB here saves the trouble of printing out a label and making the cutouts.

Power is from three AA cells; this is stepped up to a nominal 5V by REG6, although, with the resistor values shown, it is more like 4.4V. That's intentional, as it reduces the current drain slightly.

As mentioned earlier, attach the battery holder to the case using screws, as the battery can be pretty heavy, and we don't want it coming loose.



The Nano is mounted via sockets, so the screw holes under it can be accessed, although in this case they are not used. A yellow sticker covers the TCXO calibration hole.

Wire the battery up to the plug that matches CON2, being very careful that the battery's negative output goes to the ground pin closest to the corner of the PCB. There is no reverse polarity protection on the board, so if you get this wrong, you could smoke it! Once you're sure that's right, plug it in, switch on S1 and check that the display comes up as expected.

The circuit will continue operating even when the cells have discharged to about 0.8V each. With fresh alkaline cells, it draws 75mA. With each cell at 1.2V (3.6V total), the current drain is 100mA, increasing as the battery voltage decreases further. Rechargeable cells could also be used.

If you'd prefer to use an external power supply, use a 5V phone charger and leave out REG6, D1, L1 and the 150kΩ and 390kΩ resistors, plus short out D1 and L1. That will apply the 5V from CON1 directly to the circuit.

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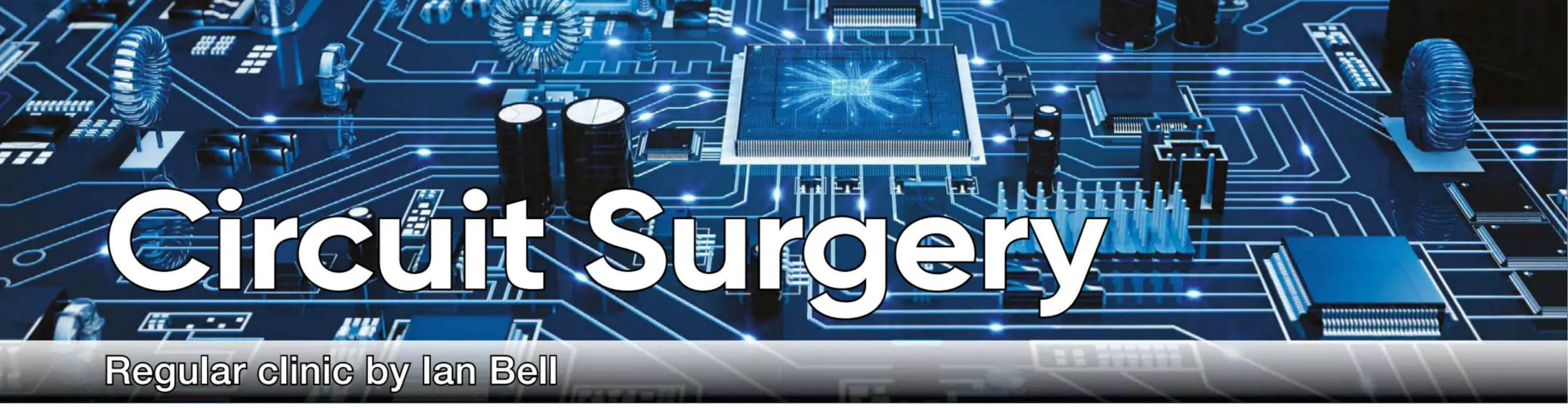


Circuit Surgery

Regular clinic by Ian Bell

Topics in digital signal processing – the sample-and-hold circuit and ADC Inputs

We are looking at various topics related to digital signal processing (DSP). DSP covers a wide range of electronics applications where signals are manipulated, analysed, generated, stored or displayed as digital data, but originate from, and/or are output as, real-world signals for interaction with humans or other parts of the physical world. Fig.1 shows the key elements of a generic DSP system with a signal path from an analogue input via digital processing to an analogue output. This does not necessarily represent every DSP system (not all have all the parts shown) but it serves as a useful reference for the various subsystems we will examine.

In the previous two articles we looked at the fundamentals of sampling and the properties of ADCs. We covered the properties of sampled signals and discussed the Nyquist-Shannon theorem and aliasing. The theorem states that if the input does not contain any frequency components at or beyond half the sampling frequency (the Nyquist rate) then it is possible to perfectly reproduce the original signal from the sample data. The antialiasing filter shown in Fig.1 is used to remove the unwanted frequencies which may cause errors. ADCs can also introduce errors or noise in the sampled representation of the signal. Quantisation noise is caused by the finite number of values the ADC's output codes can take (2^N values for N bits) and occurs even with an ideal ADC. Real ADCs have a number of non-ideal characteristics, which we discussed last month, which can add additional errors.

The discussion so far has not covered all aspects of the process of getting an analogue signal into digital form. The signal is commonly captured at the required sample times by a sample-and-hold circuit (as shown in Fig.1). The basic principle here is that for an ADC to perform a conversion it needs the analogue input voltage to be constant for a certain amount of time, which will depend on the implementation of the ADC. If the input voltage changes significantly during this time then errors may occur in the conversion. The sample-and-hold block, which is usually part of the ADCs input circuit, performs this task.

If the input signal changes very slowly with respect to the ADC's operating speed, the voltage change may not be significant, and the sample-and-hold circuit may not be needed. However, in many ADC applications expected changes in the input voltage will result in errors if there is no sample-and-hold circuit. For example, a successive approximation converter (a common type of ADC) uses an internal digital-to-analogue converter (DAC) to compare an analogue version of the digital output code with the input voltage. As the name suggests, it improves the accuracy of the digital code in successive steps using the comparison to decide on each output bit in turn from most to least significant. If the input voltage changes during the conversion the partially complete digital code will not be compared to the same input value on each step, causing errors in the final result.

Sample-and-hold circuit characteristics

As with any circuity, the sampling process may be subject to non-ideal characteristics, which in this case can introduce errors into digitised representation of the signal. Problems can occur due to both inaccuracies in the sample timing and value (voltage) of the sampled signal.

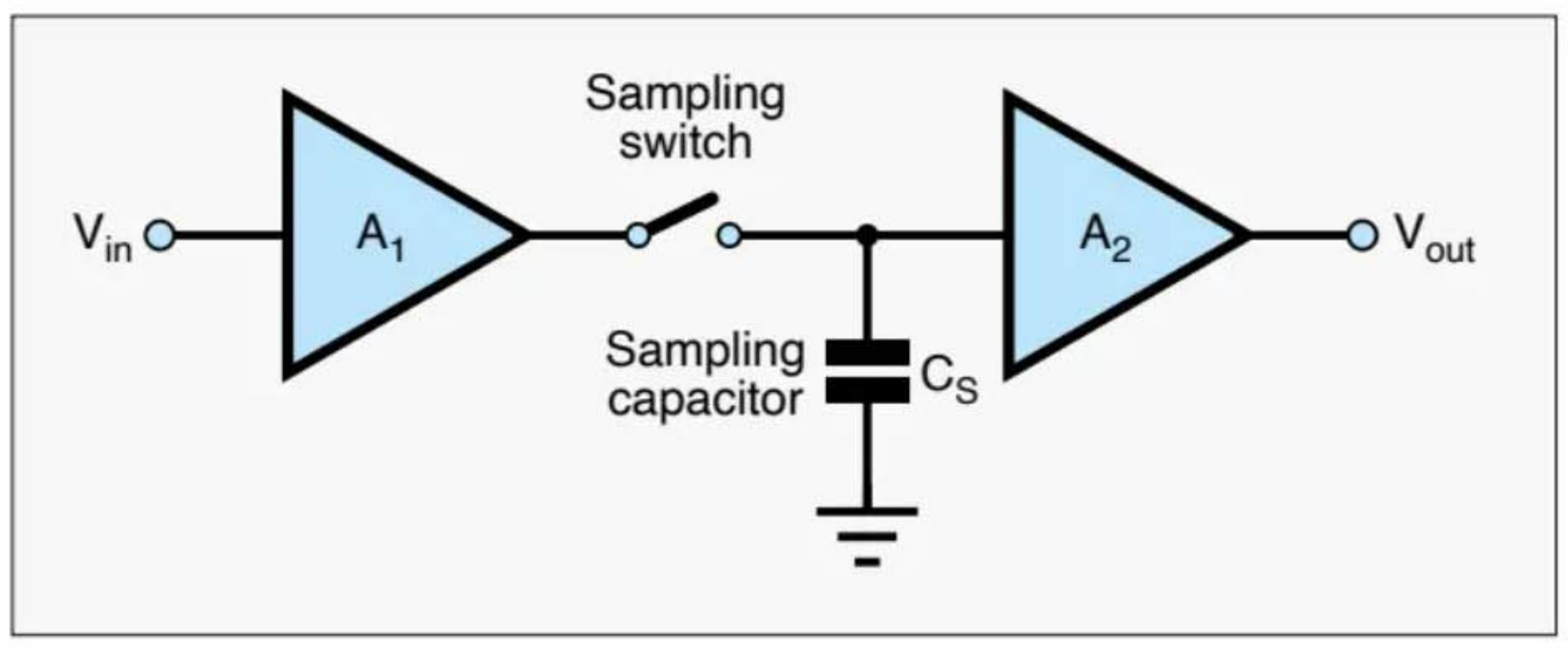


Fig.2. Basic sample-and-hold circuit.

A basic sample-and-hold circuit is shown in Fig.2. As noted, this will often be included on the ADC chip (or as part of a microcontroller's ADC subsystem). However, separate sample-and-hold chips are available. The performance of a typical ADC will depend on the characteristics of the built-in sampling circuit and its interaction with external circuitry; therefore, it helps to be aware of the process when using ADCs. The characteristics of the sampling circuit are usually covered in ADC datasheets.

The sampling circuit is essentially a switch and a capacitor, as seen in Fig.2. The switch is electronic (eg, a MOSFET). In Fig.2, A_1 is typically the external circuitry driving the ADC. It may be an amplifier, but does not have to be, for example it could be a potential divider connected to the ADC's input. Typically, A_2 represents the input part of the ADC's conversion circuitry. In a separate sample-and-hold device, A_1 and A_2 could be buffer amplifiers designed to provide high-performance operation. When the sampling switch is closed A_1 directly drives C_S, so the voltage on C_S will follow v_{in} – that is, it will track changes in v_{in}. For this reason, this circuit is also referred to as a 'track and hold'. When the switch is closed the capacitor will retain (hold) whatever voltage was on it at the instant the switch opened.

The circuit in Fig.2 is idealised (assuming the components are ideal). In reality, we need to consider

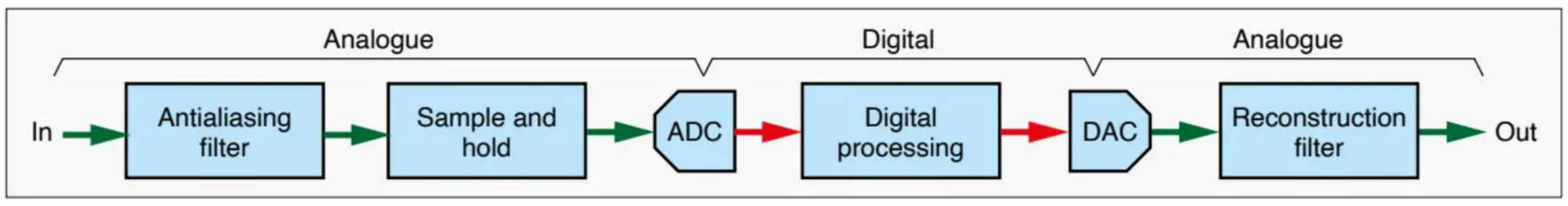


Fig.1. Generic DSP system structure.

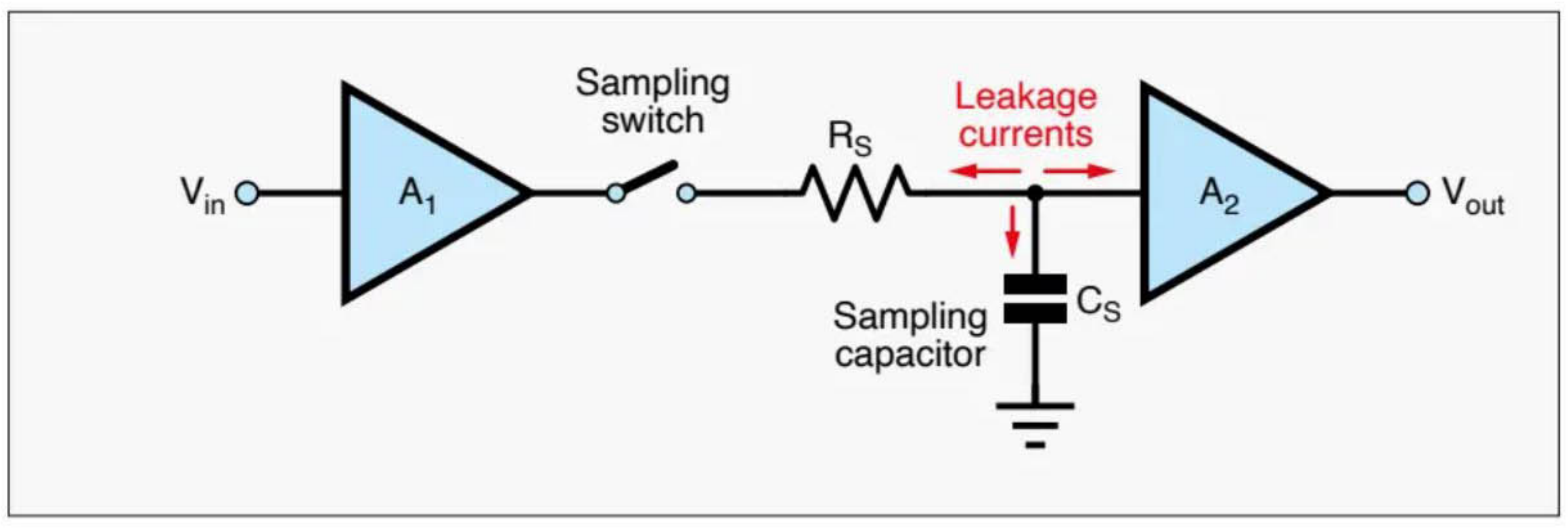


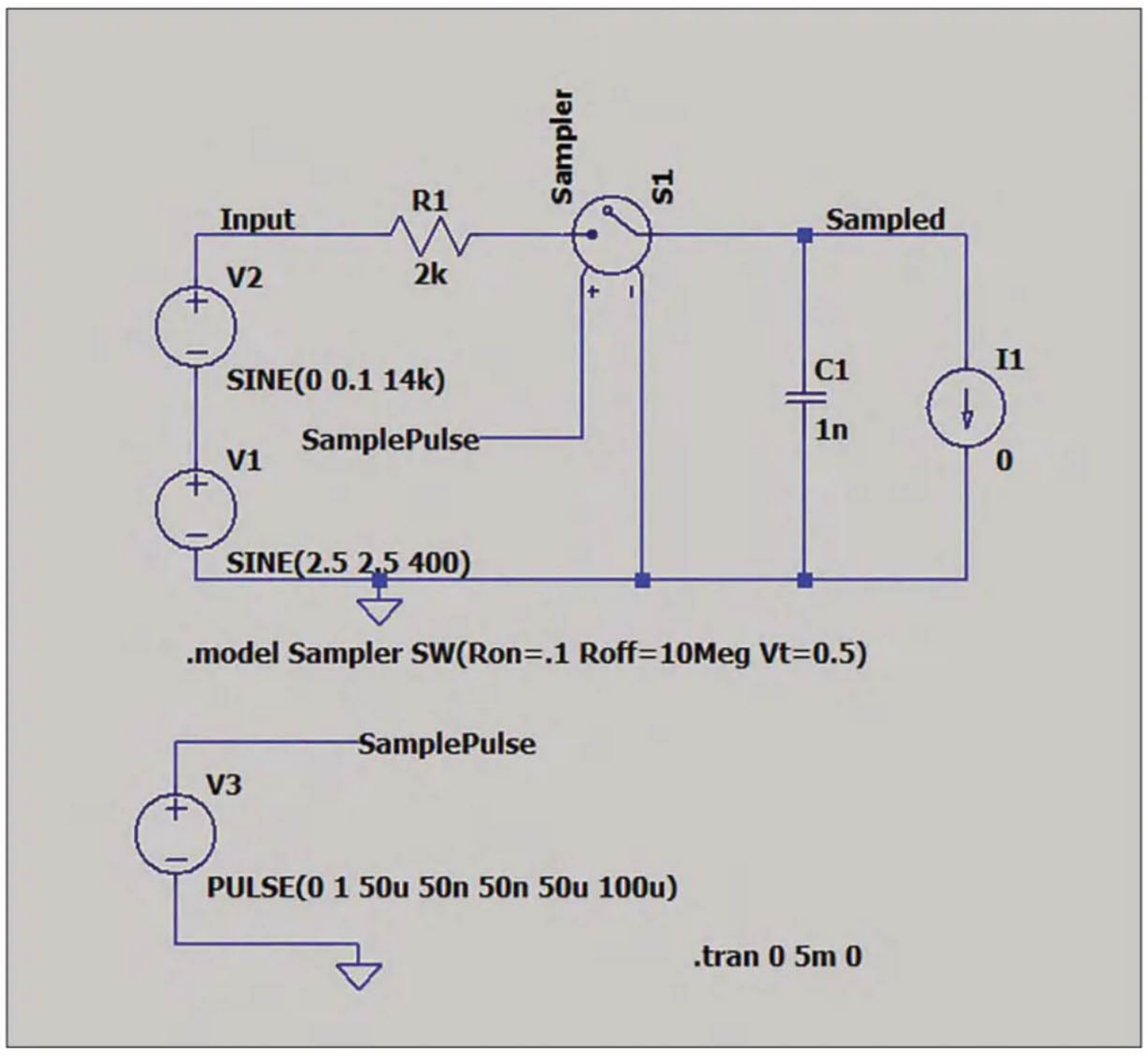
Fig.3. Sample-and-hold circuit with some non-ideal characteristics.

additional parameters. There will be resistance (R_S) between the source of the signal being sampled and the sample capacitor (see Fig.3). This, together with the sample capacitor, will influence how long it will take after the sample switch is closed for the capacitor to charge to the input voltage in order to obtain an accurate sample value. There will also be leakage currents which will change the voltage on the sample capacitor over time, limiting the time which the sample can be accurately held for. There may be other mechanisms causing potential errors in sampling circuits. For example, a MOSFET sampling switch can couple the control signal to, or inject charge into, the sampling capacitor.

Sampling and holding simulation

Fig.4 shows an LTspice circuit based on Fig.3. The sampling capacitor is `C1` and the input series resistance is `R1`. The leakage current is modelled with the `I1` current source, which is configured for the ideal case (zero current) in Fig.4. The switch is close to ideal (on resistances much smaller than `R1`, off resistance very large at 10MΩ). The switch is controlled by the 1V `SamplePulse` waveform from `V3` (the switch threshold is 0.5V). This is simply a square wave which will put the circuit alternately into track and hold modes. The circuit values, signals and timing in the circuit in Fig.4 are to illustrate the principle of operation and are not related to any particular ADC or sampling system.

The results from the simulation in Fig.4 are shown in Fig.5. The sampling waveform (cyan trace) has been scaled and shifted with a formula for convenience of showing alongside the signals and labelled with the track and hold conditions. The input waveform (green trace) is the sum of the two sinewaves from `V1` and `V2`. The output waveform (red trace) can be seen to follow the input when the circuity is in track mode. The output is constant during the hold periods, with a value equal to the input at the start of the hold period. In a DSP system the ADC would perform conversions on the held signal.



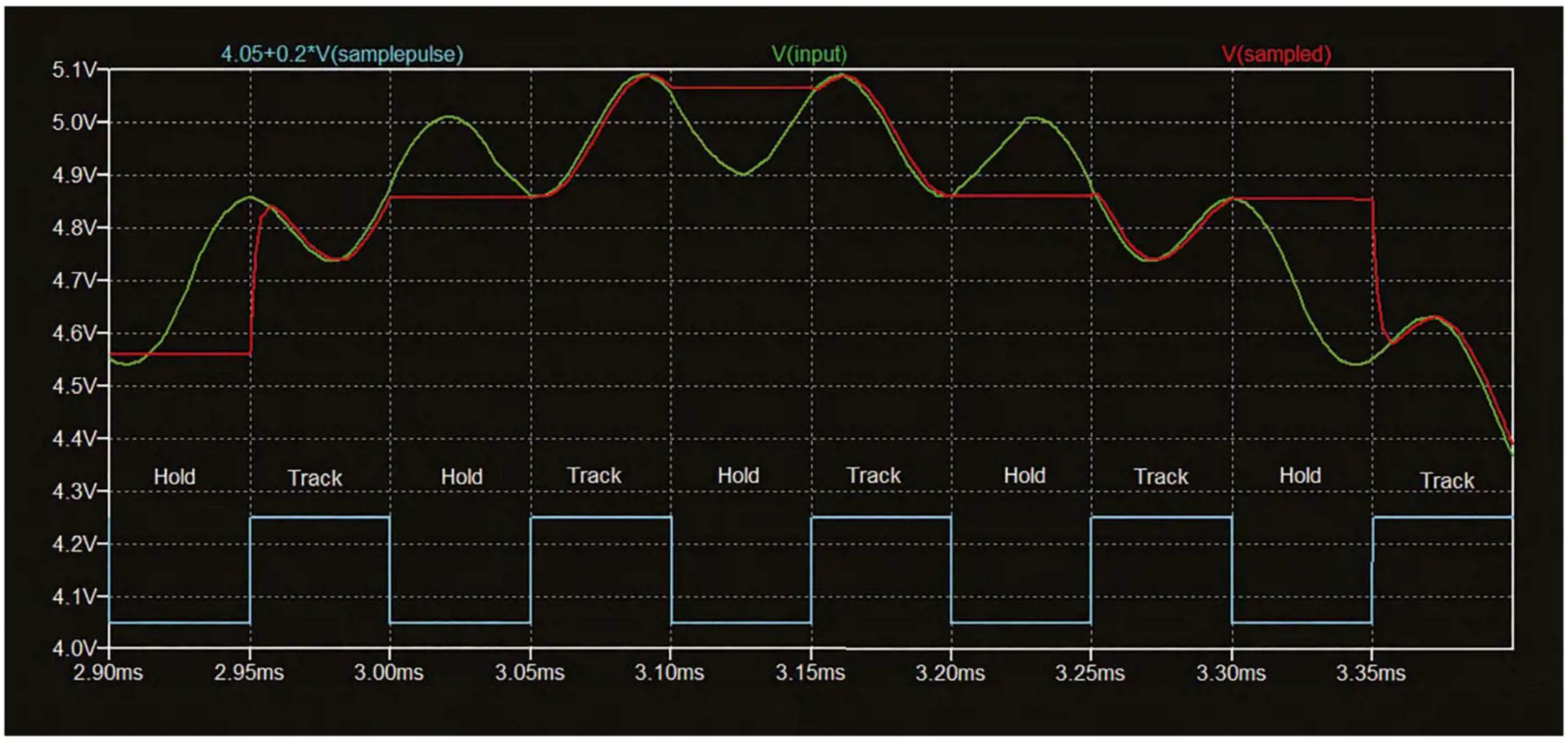
```
SINE(0 0.1 14k)
SINE(2.5 2.5 400)
.model Sampler SW(Ron=.1 Roff=10Meg Vt=0.5)
PULSE(0 1 50u 50n 50n 50u 100u)
.tran 0 5m 0
```

Fig.4. LTspice schematic to illustrate sampling onto a capacitor.

Fig.6 shows a zoom in from Fig.5 on the first hold to track transition. This shows that the output voltage does not immediately equal the input voltage when the circuit enters track mode. The sampling capacitor has to charge (or discharge) from the previous hold voltage to the current input voltage. The time taken depends on the *RC* time constant and the amount of voltage change, and is referred to as the sample-and-hold's 'acquisition time'. After acquisition the output will follow the input unless the input changes too fast for the voltage on the capacitor to follow (again related to the time constant).

Fig.7 shows the effect of leakage current. This uses the circuit in Fig.4 with the leakage current source `I1` set to 1µA. Leakage current can flow via the sampling switch (non-infinite off resistance), into the next circuit stage (A_2 in Fig.3) or via the capacitor's imperfect dielectric insulation. Leakage results in a progressive change (droop) in the held voltage, as can be seen by comparing the waveforms in Fig.5 and Fig.7. Droop rate is the rate at which voltage on the sample capacitor changes during the hold interval. It is determined by I_L/C_S where I_L is the leakage current, and C_S is the sampling capacitance. Note that a constant leakage current results in a linear voltage change on the capacitor unlike the nonlinear change when charging through a resistor.

Fig.5. Waveforms from the LTspice circuit in Fig.4 (`I1` is zero).



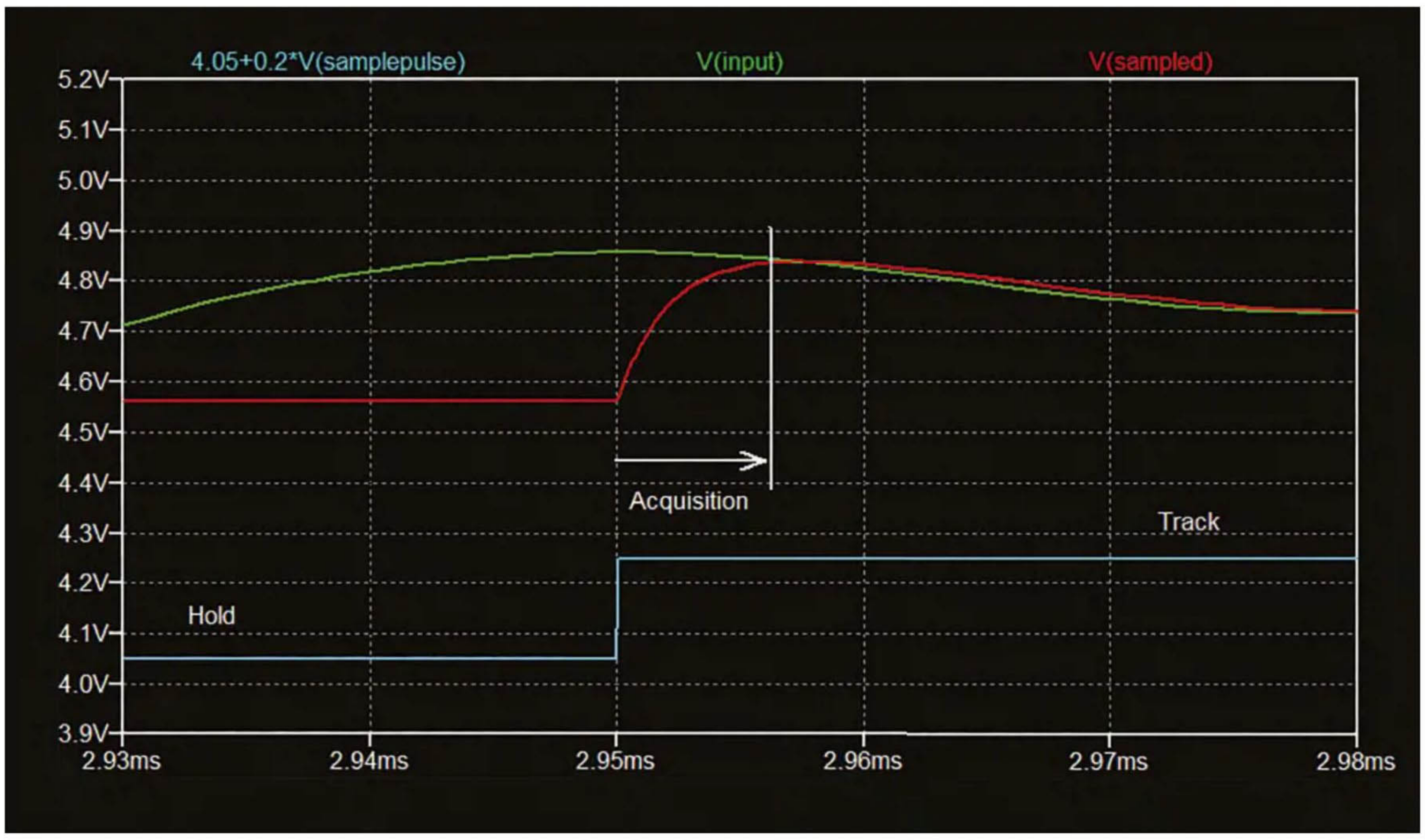


Fig.6. Zoom in on waveforms in Fig.5 to show signal acquisition on the sampling capacitor.

Sample-and-hold circuit timing

Fig.8 shows characteristics of the sampling process. The sampling switch is controlled by the sampling clock, which instructs the sample-and-hold circuit to change between the sample (track) and hold modes. When the switch is closed, sampling begins and the capacitor will charge to the input voltage, this takes a finite time – the time required by the sample-and-hold circuit to acquire the sample value. The more accurately you need the capacitor voltage to match the input voltage the longer you have to wait (all other things being equal).

We can define the 'acquisition time' (t_{ACQ}) as the duration from the end of the hold state (sampling begins) and the point at which the voltage on the sampling capacitor settles to within 1 LSB of the input voltage. With reference to Fig.3 and Fig.8, acquisition time is then given by:

$$t_{ACQ} = R_S C_S \ln(2^N)$$

Here, N is the number of ADC bits. This is an application of the standard RC charge/discharge equation:

$$t = RC \ln\left(\frac{V_{final}}{V_{initial}}\right)$$

where the ratio of final to initial voltage is the worst case – the entire ADC input range (2^N).

Once the input voltage has been acquired, the sample-and-hold circuit can enter the hold state to allow conversion to take place. Again, this is controlled by the sampling clock. The relevant clock edge represents the time at which the command to hold is given. The circuit will take a finite time to actually enter the hold state (and hence take the sample). This is called 'aperture delay' (t_{AD}).

Relating ADC and sample-and-hold circuit characteristics

The performance of the sampling process depends on both the sample-and-hold circuit and the ADC. If the sampling is of insufficient capability compared with the ADC then it may undermine the quality of the digitised signal. Two key ADC parameters, which we discussed last month, are the conversion time and the LSB. We will briefly recap these.

The 'conversion time' (t_{C}) is how long it takes from a conversion being initiated and the data becoming available. If conversions are performed continuously the conversions time indicates the maximum number of conversions per second that can be performed (sample rate). In the simplest case, sample rate will be $1/t_{\mathrm{C}}$, but it is not always that simple. Some converters (eg, pipelined ADCs) have a faster sample rate than $1/t_{\mathrm{C}}$ because processing of multiple step-by-step conversions occurs simultaneously. In such cases there is a latency of several

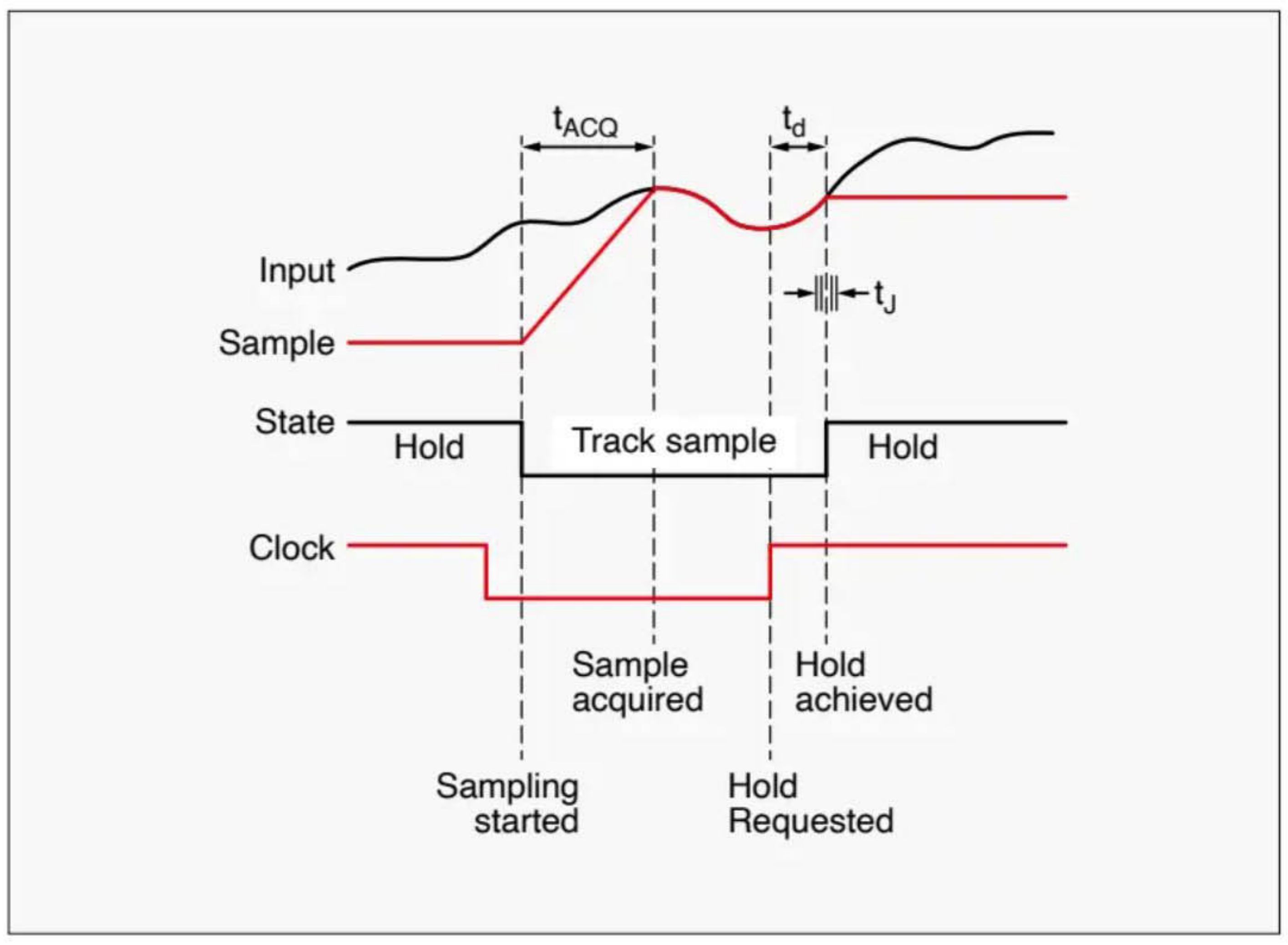


Fig.8. Sample-and-hold circuit timing characteristics.

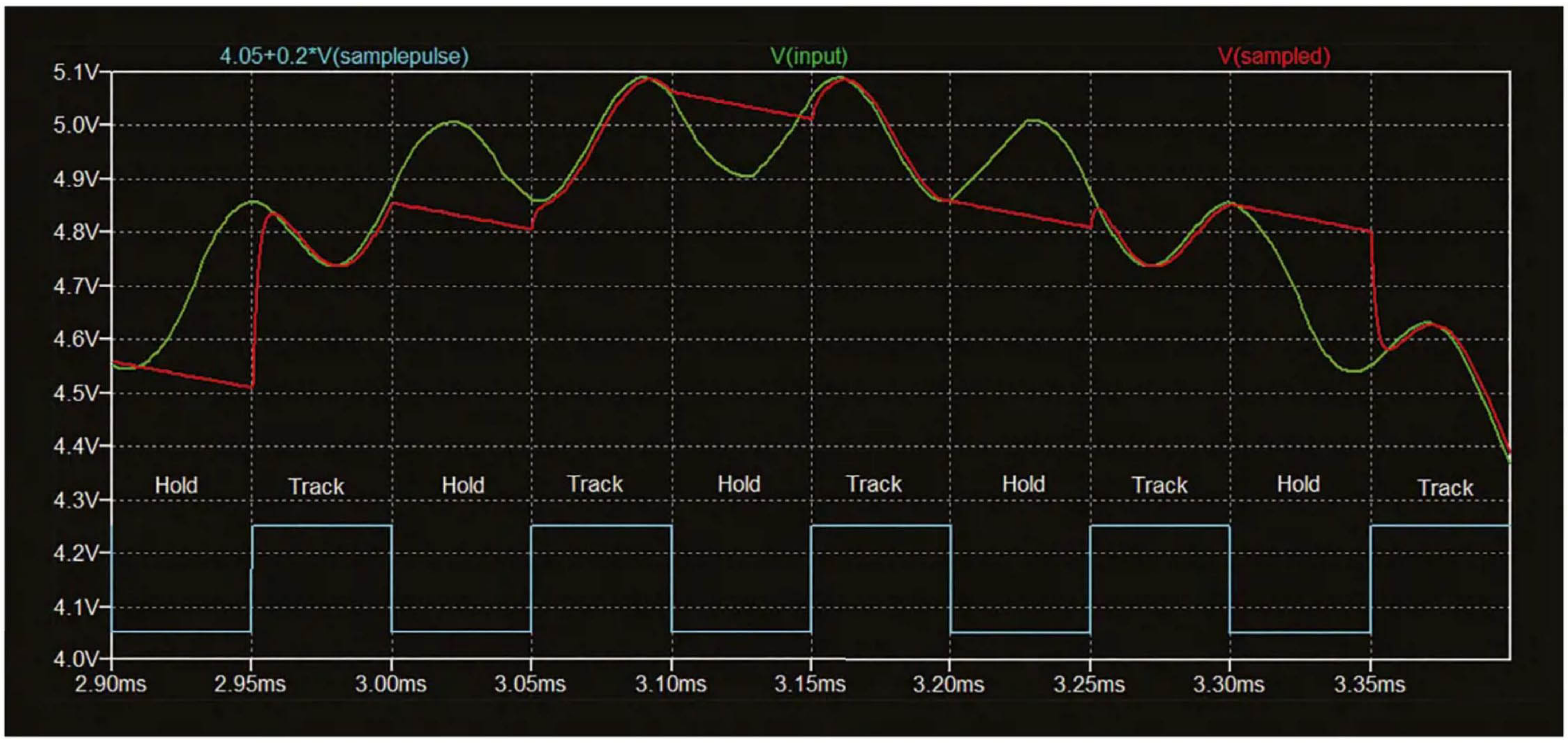


Fig.7. Waveforms from the LTspice circuit in Fig.4 (`I1` is 1µA).

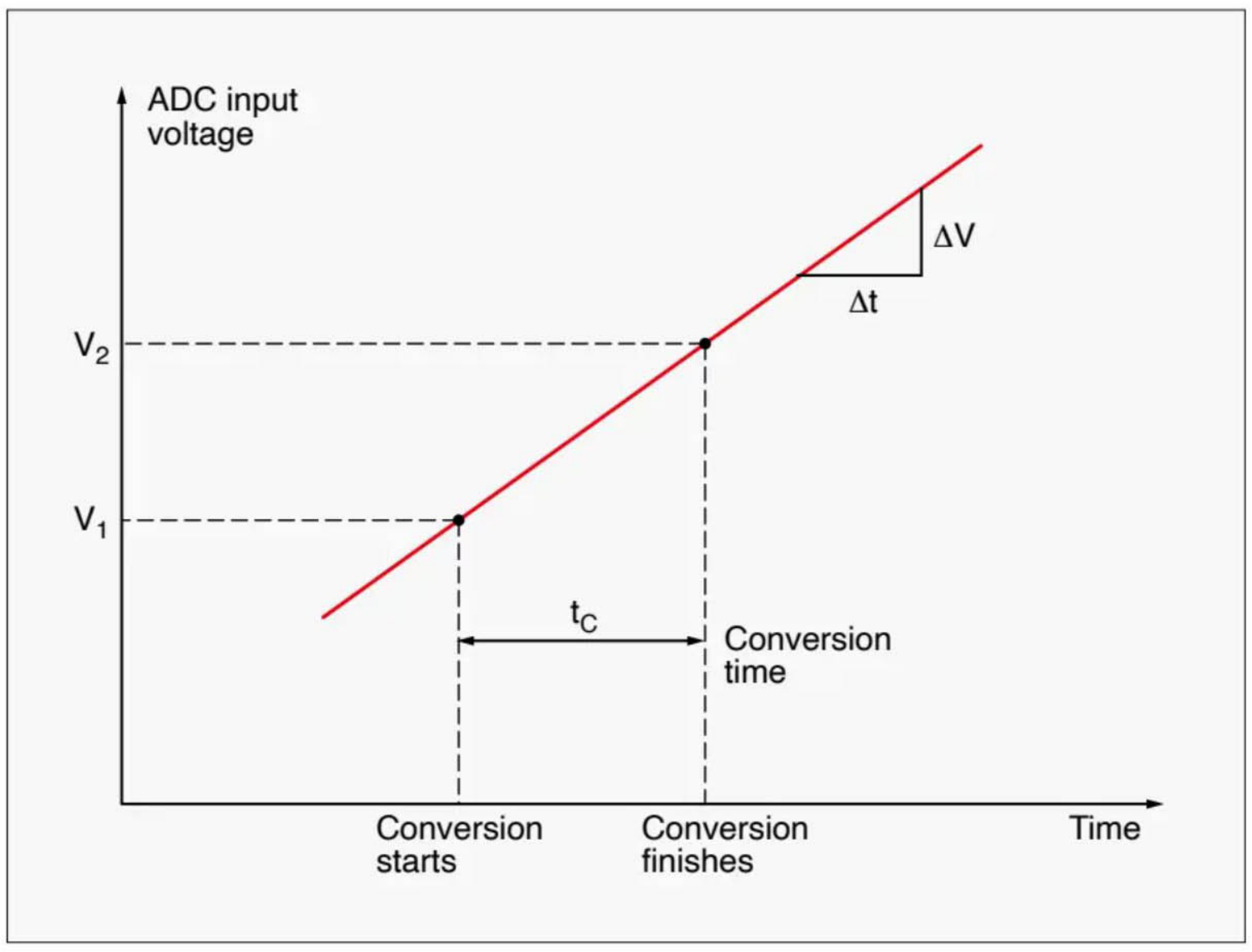


Fig.9. Changing input signal to an ADC without a sample-and-hold circuit.

conversion cycles before the result of a particular conversion is available.

The least-significant bit (LSB) is the input change that the ADC can resolve, that is the smallest input change required for a change in code output. Last month, we saw that:

$$LSB = \frac{range}{2^N}$$

where the ADC's input range is defined as $V_{\text{RefH}} - V_{\text{RefL}}$, the difference between the upper and lower reference voltages. N is the number of bits. LSB and conversion time can be related to sample-and-hold circuit parameters – faster conversion and more bits (smaller LSB) generally require higher performance sampling circuits.

The need for sample-and-hold circuits

Fig.9 shows a graph of input voltage against time for an ADC for which there is no sample-and-hold circuit. We assume the conversion takes time t_C, during which the input changes from V_1 to V_2. If this change ($V_2 - V_1$) is larger than one LSB then the conversion may be disrupted. Fig.10 shows the same situation with a sample-and-hold circuit (similar to Fig.6) for comparison.

For a changing input voltage, the possibility of error depends on the relationship between the rate of change of voltage and the conversion time. The rate of change of input voltage is the voltage difference ΔV divided by the time taken for that change Δt (ie, rate = $\Delta V/\Delta t$), as shown in Fig.9. The symbol Δ (delta) means 'change of'. Measuring the rate as shown on Fig.9 is fine for a constant rate of change, but for real signals, where the rate changes constantly, we use the calculus form given by: rate = $\mathrm{d}V/\mathrm{d}t$, which simply implies measurement of the rate over an infinitely short time interval.

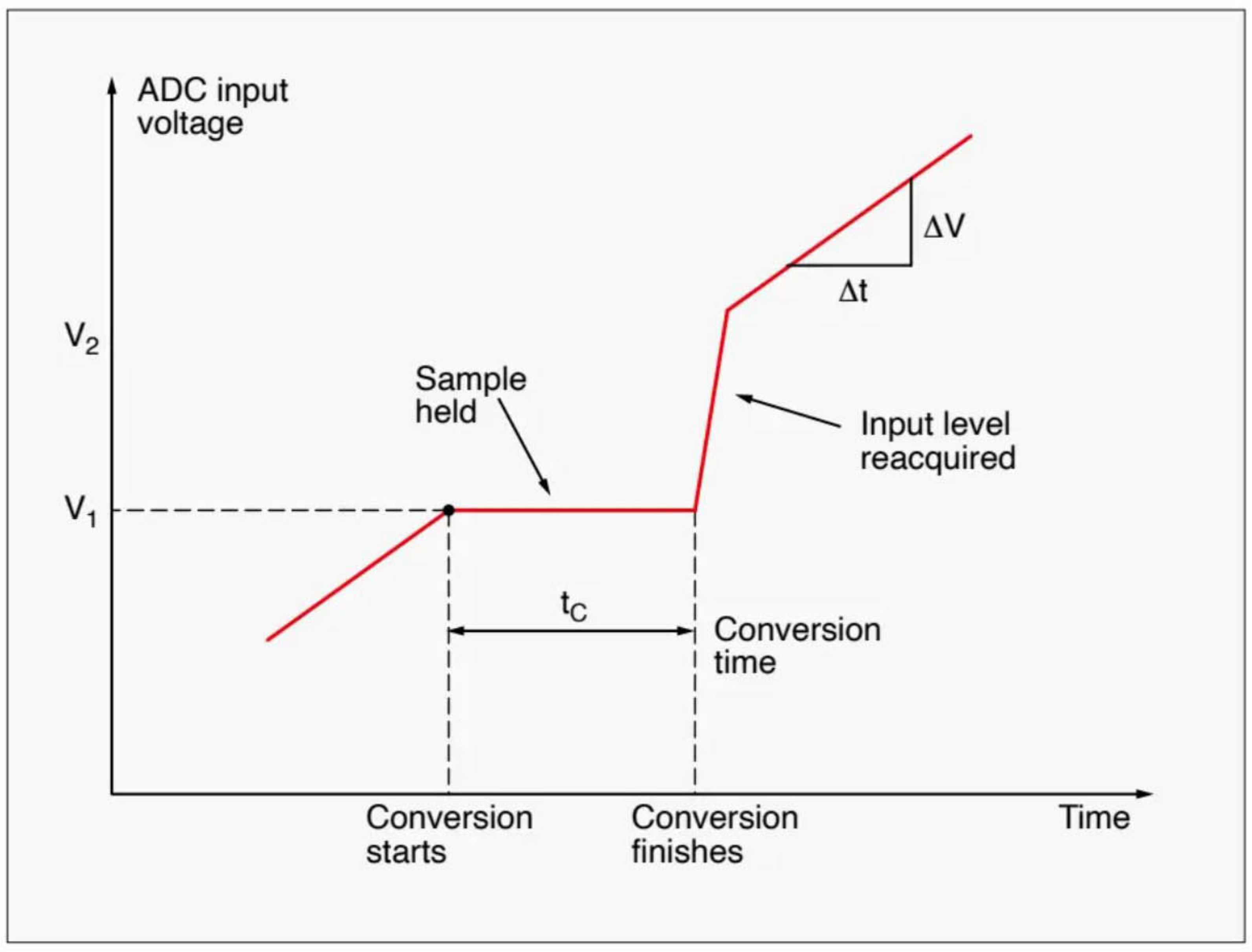


Fig.10. ADC input with sample-and-hold circuit for comparison with Fig.9.

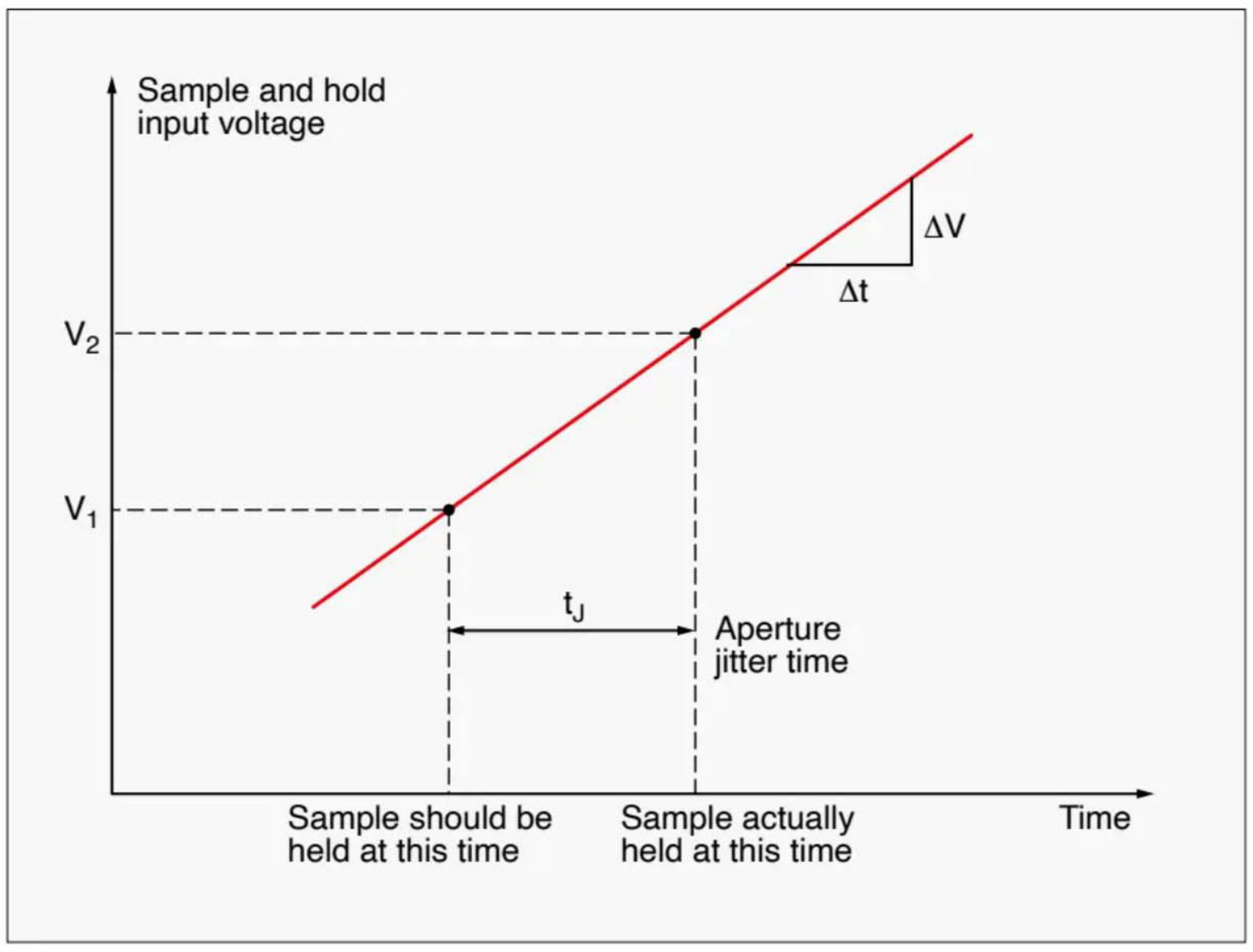


Fig.11. Aperture Jitter timing.

If we multiply the maximum rate of change of a signal by the conversion time we can find the largest amount the input signal changes during this time, which must be less than the LSB to prevent errors. We can write this mathematically as:

$$t_c \frac{dv_{in}}{dt} \leq LSB$$

An obvious question at this point is how we know what rate of change value to use. We should probably look at the most

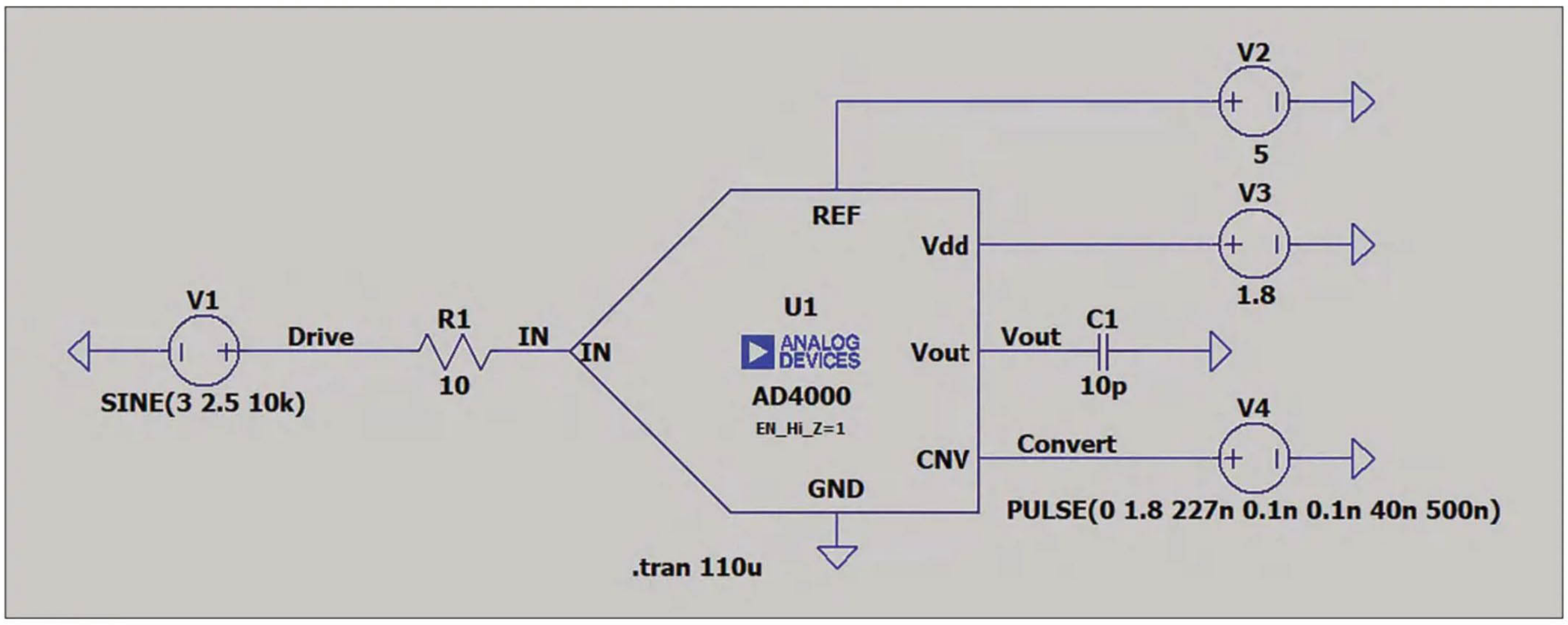


Fig.12. Circuit for AD4000 ADC simulation in LTspice.

demanding case and one way to do this to consider a sinewave at the highest frequency present in the input signal. Our input can be written:

$$v_{in} = A\,sin(2\pi f t)$$

where f is the frequency in hertz and A is the amplitude (peak). To find the rate of change we use calculus to differentiate the signal function (find $\mathrm{d}v_{\mathrm{in}}/\mathrm{d}t$). Readers familiar with calculus will know that differentiating a sine function gives a cosine function; so we get:

$$\frac{dv_{in}}{dt} = 2\pi f A\,cos(2\pi f t)$$

The maximum value of a cosine function is 1, so the maximum rate of change is $2\pi fA$. We can use this figure in the calculation given above to determine if a sample-and-hold circuit is required. This may not seem like a major issue as most ADCs will have the sampling system anyway; however, the same approach can also be used with other converter timing issues as we shall see shortly. Furthermore, an understanding of the behaviour of the sampling process is useful when working with ADCs, for example it helps to know that if you drive an ADC's input from a source (eg, a sensor) with a high internal resistance then that resistance will increase the acquisition time, which may cause errors.

Simulation files

Most, but not every month, LTSpice is used to support descriptions and analysis in *Circuit Surgery*.
The examples and files are available for download from the *PE* website: https://bit.ly/pe-downloads

Jitter

DSP systems typically have a constant frequency sample clock, rather than taking samples at arbitrary times (eg, one-off

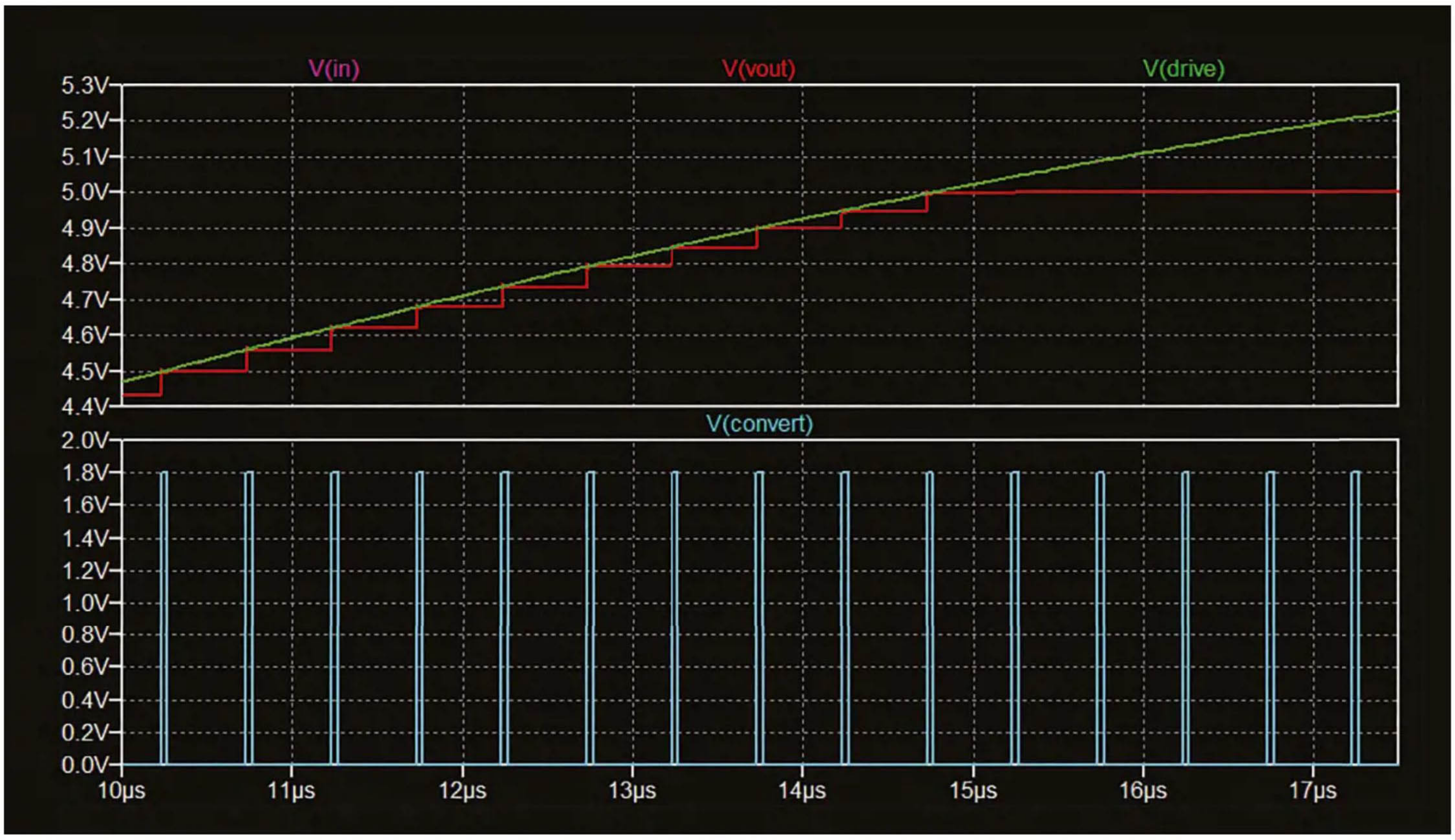


Fig.13. Results from circuit in Fig.12.

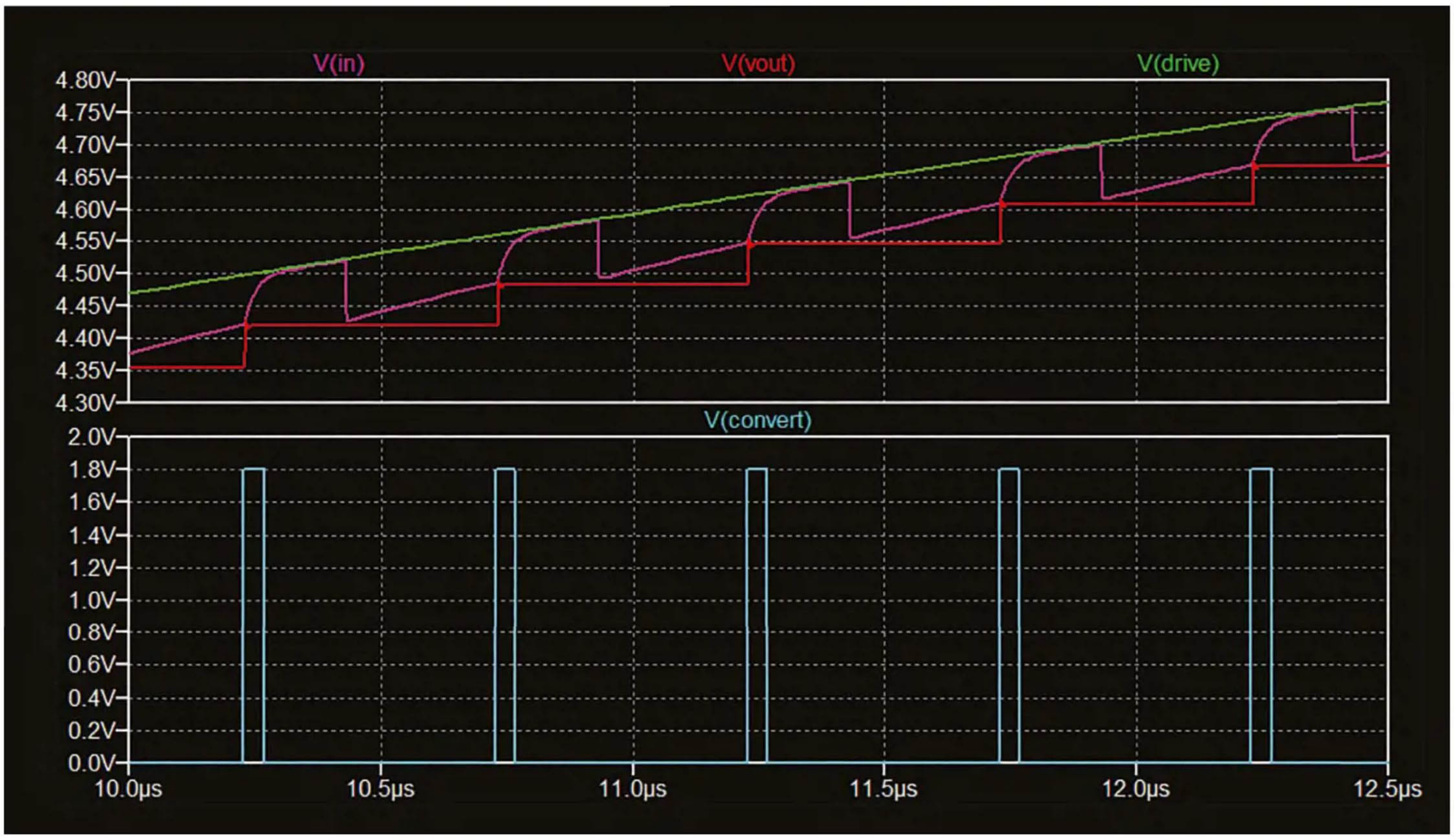


Fig.14. Results from circuit in Fig.12 with `R1` changed to 10kΩ.

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measurements controlled by a user). In such cases variations in the aperture delay between clock cycles, or in the clock edge timing itself, will cause a change in effective sample time in each cycle. This is referred to as 'aperture jitter' (t_J) The term 'clock jitter' is used to refer to timing variations specifically in clock signals.

Sampling at the wrong time point means that the wrong voltage will be converted. The voltage deviation resulting from aperture jitter will show up as noise in the sampled signal. The problem gets worse for higher input signal frequencies because the signal voltage will change more in the jitter time. Thus, aperture jitter is a critical characteristic in ADCs used for high-frequency signals.

In order for the aperture jitter of the sample-and-hold circuit not to cause conversion errors the change in signal voltage (V_{in}) during the jitter time (t_J) must be less than the LSB. This is similar to the problem discussed earlier about the need for a sample-and-hold circuit (see Fig.11), except now we use aperture jitter rather than conversion time, so we need:

$$\frac{dV_{in}}{dt} t_J < \frac{range}{2^N}$$

For a sinewave with a peak value A equal to half the ADC range (the peak-to-peak sinewave covers the entire input range, ie, $range = 2A$) we have, using the maximum rate of change of sinewave calculated above, the following:

$$2A\pi f t_J < \frac{2A}{2^N}$$

So

$$t_J < \frac{1}{2^N \pi f}$$

For example, CD audio uses 16 bits at a sample rate of 44.1kHz. This means the highest input frequency must be limited to below 22.05kHz (if we a have perfect anti-aliasing filter). This is a requirement of sampling theory discussed previously – the highest frequency present in the input must be less than half the sampling frequency otherwise aliasing will occur in the sampled data.

The above formula indicates a maximum aperture jitter of 220ps (picoseconds) and illustrates that aperture jitter requirements can be quite demanding. A sample rate of 44.1kHz is around one sample every 23µs – about one hundred thousand times longer than the indicated maximum aperture jitter time. However, the above calculation is probably somewhat pessimistic about the aperture jitter requirements as most of the content of a real audio signal will be at lower frequencies and any higher frequencies present will generally not be near maximum amplitude.

ADC simulation

So far we have not looked at an LTspice simulation of an ADC, however, there are models of several ADCs included in the downloaded library. These models have analogue outputs which represent the quantised signal – they do not provide the digital bits. This is because LTspice is not aimed at modelling digital (or mixed analogue and digital) systems, so providing many digital outputs for the code would not be particularly useful. Some digital signals are modelled, for example the start convert control input. The models focus on the input section and allow aspects such as the impact of the input circuit on the acquisition to be investigated. Noise and FFT simulations can also be performed.

Fig.12 is similar to the example circuit for the AD4000 provided by Analogue Devices. The AD4000 is a 16-bit 2 MSPS, Precision, Pseudo Differential, successive approximation register ADC. The simulation circuit includes the device power supply (1.8V) and reference voltage (5V). Conversion is started by a rising edge on the `CNV` input, which is driven by a pulse waveform in the simulation. The input is a sinewave configured to exceed the reference voltage. The AD4000 has input overvoltage protection – not all ADCs do, so make sure that you are aware of the maximum ratings of any device you are using.

The results from Fig.12 are shown in Fig.13. We see the output update after each conversion start pulse and we can see the quantisation of the output (red trace is stepped). When the input (green trace) exceeds the reference voltage the output remains at the maximum output value. The drive and ADC input voltages are equal, which indicates there is no significant interaction between the ADC input and external circuitry. Fig.14 shows the results with the input resistor changed to 10kΩ. Here we see the ADC input is not the same as the drive voltage from the `V1` source – the input voltage changes as the ADC's sampling switches change state. This is a simple example but illustrates how the ADC model can help evaluate the driver circuit providing input to the ADC.

Introduction to LTspice

Want to learn the basics of LTspice? Ian Bell wrote an excellent series of *Circuit Surgery* articles to get you up and running, see *PE* October 2018 to January 2019, and July/August 2020. All issues are available in print and PDF from the *PE* website: **https://bit.ly/pe-backissues**

AOShop

The home for specialist audio, analogue and historic components – provided by Jake Rothman, *PE's Audio Out* columnist. The AOShop is your best bet for classic analogue 'NOS' (new old stock) components, including all parts for *Audio Out* projects and designs.

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Holco H2 2.2MΩ 1W, 1%	£1.00
Welwyn 1GΩ 2W	£1.00
5k Bourns 3321H cermet trimmer	£0.50

Potentiometers

Bourns 81	
25kΩ lin cermet	£2.00
25kΩ lin, 5kΩ lin conductive plastic	£3.00
Bourns 91	
10k dual-gang lin or log	£10.00
Plessey moulded-track	
5kΩ log with switch	£3.00
50kΩ A/log	£3.00
Mil 250kΩ lin dual	£5.00
Alpha	
16mm 4.7kΩ A/log	£0.80
220kΩ A/log	£0.80
10kΩ lin centre-detent dual-gang	£1.50
Allen Bradley J series/Honeywell	
10kΩ lin 1 million cycles	£5.00
Blore Edwards AB 45 dual 5kΩ A/log with switch	£3.50
Alps RK9 dual-gang 5kΩ RD law	£4.00
Alps 50k log tapped motorised stereo	£5.00
BI P260 500kΩ log conductive plastic 1 million cycles	£2.00
Colvern wire-wound 100kΩ or 50kΩ dual-gang 3W	£5.00
Mil Spec hermetic 10Ω	£8.00

Miscellaneous

Theremin Clearance Sale!	
Elysian Theremin MIDI box	£300
PCBs	
Pocket Theremin (*EPE*, 1996)	£2.00
Elysian Theremin (*EPE*, 1996)	£6
Synth VCF, VCO (*EPE*, 2017)	£3.00
48V PSU (*EPE*, 2019)	£3.00
SMT dual transistor adapter	£0.40

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AUDIO OUT

By Jake Rothman

Switching in audio equipment – Part 2

This month, we carry on from where we left off in June and finish our look at the many varied types of *mechanical* audio switches.

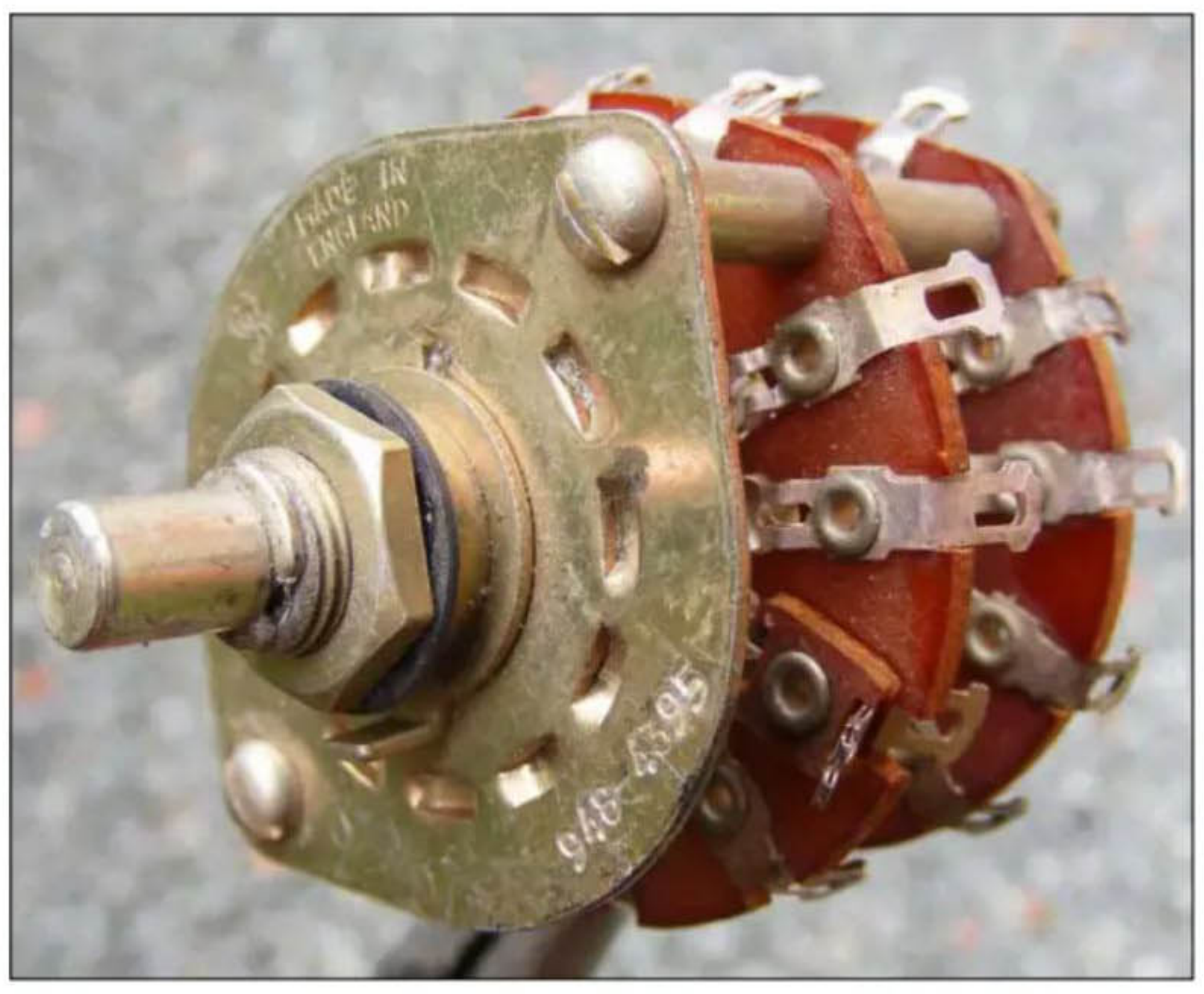

Fig.21. Rotary wafer switches have been around since the swinging 1920s. They have very long life, are easy to service but are labour intensive to wire.

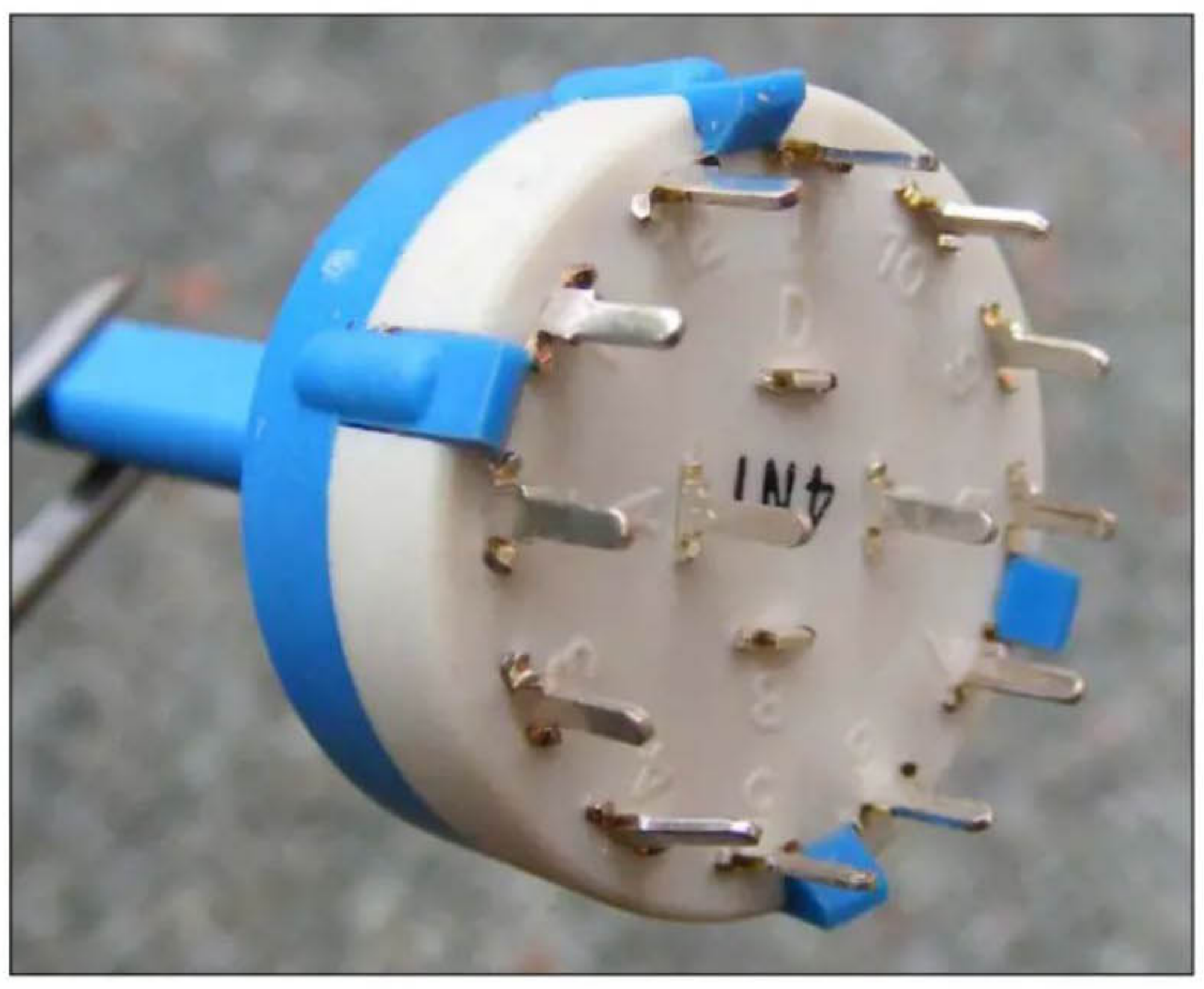

Fig.22. Lorlin/Alpha standard pattern rotary switch, 6-way 2-pole. These are available in both BBM and MBB versions and are well sealed.

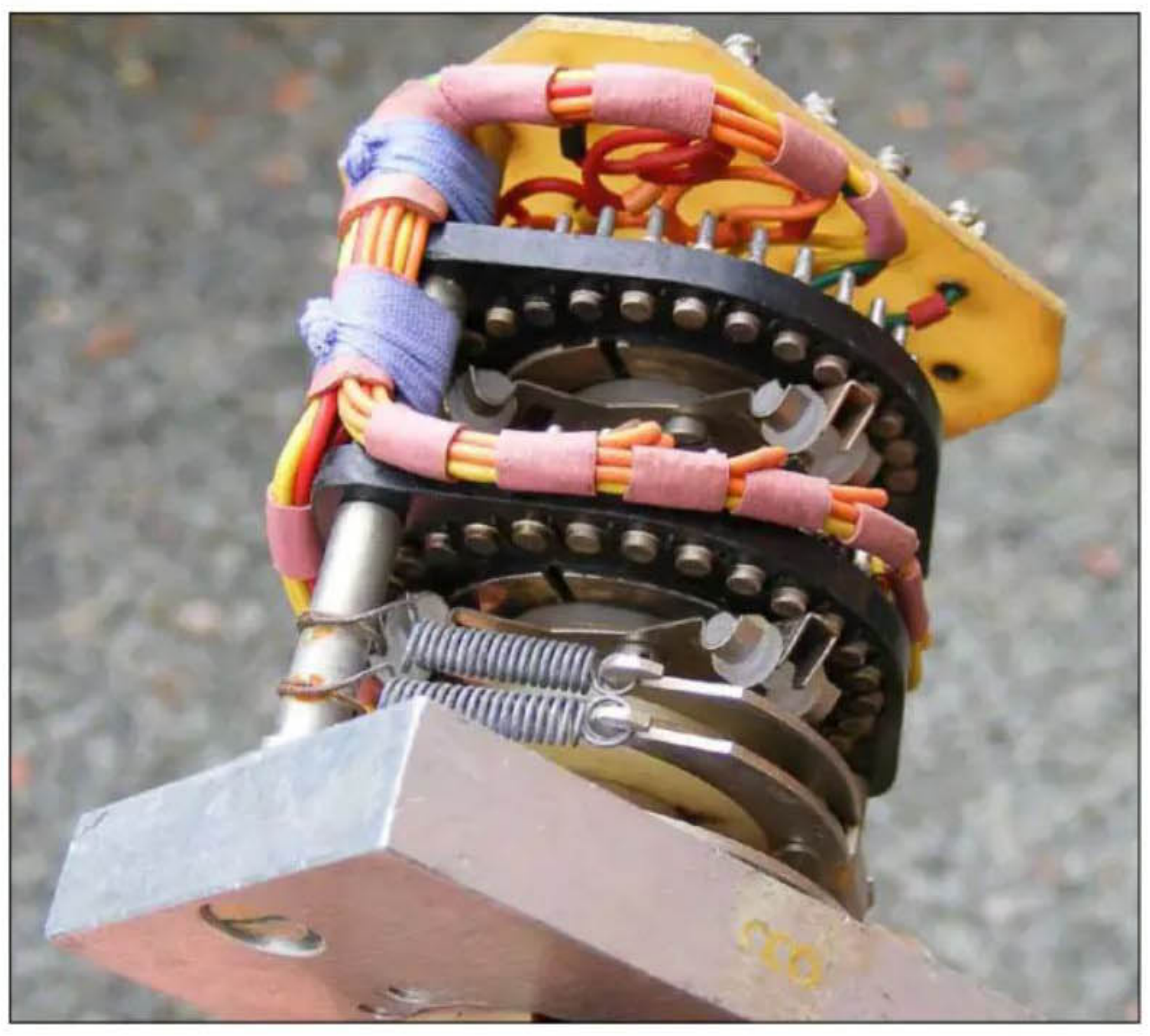

Fig.23. Some rotary switches are beautiful pieces of mechanical engineering. Such as this Plessey 72 series military switch.

The Rotary Club

Rotary switches, sometimes called wafer switches (Fig.21), are the most versatile, but often require a lot of costly hand-wiring; although this is not really a problem for home constructors and prototypes. The old Paxolin wafer types have an open construction which means they easily get dirty but are also very easy to clean. It is even possible to buy kits, such as the RS Maka-Switch to assemble your own specialised multi-wafer switches. (These are popular among older engineers who played with Meccano as kids!)

Most PCB-mounting types are expensive and have unique overlays and pinouts. I use the Lorlin pattern types (Fig.22) which are also dual sourced by Alpha and have a standard pin-out. These have a washer under the nut to set the number of ways.

The military and aviation sectors seem to favour rotary switches for their ruggedness (>100,000 cycles) compared to lightweight slide switches for example. Those made by Plessey, Painton, Diamond H, Elma and Greyhill are the best and come in up to 29-way and eight-wafer (or 'bank') options. They are often used as switched attenuators in audio and can cost between £20 and £100 each. A fine example is shown in Fig.23.

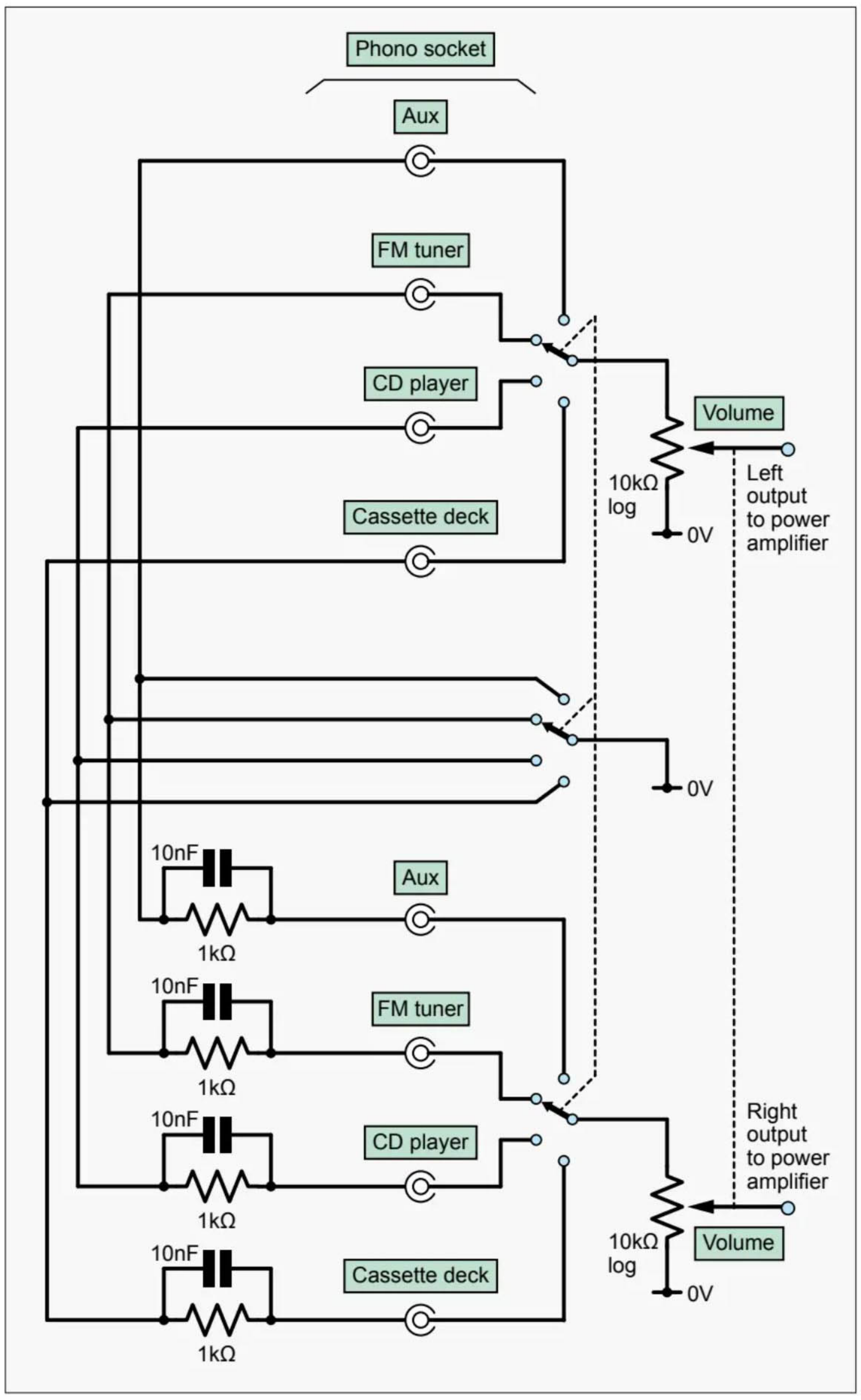

Fig.24. Circuit for rotary Hi-Fi selector switch. On some more complex designs, the earth connections are also switched as well to minimise earth loops.

The selector switch on Hi-Fi amplifiers is traditionally a multi-position rotary switch. In switch parlance the number of positions is the number of 'ways'. The number of sections is the number of poles. A typical amplifier selector switch circuit will have four ways and two poles (one section for each left and right channel) as shown in Fig.24. A useful dedicated (standalone) audio source selector box is shown in Fig.25.

Crosstalk

A common problem with selector switches is crosstalk. This is where a signal from an unwanted source bleeds into the selected source. An example of this happening is when listening

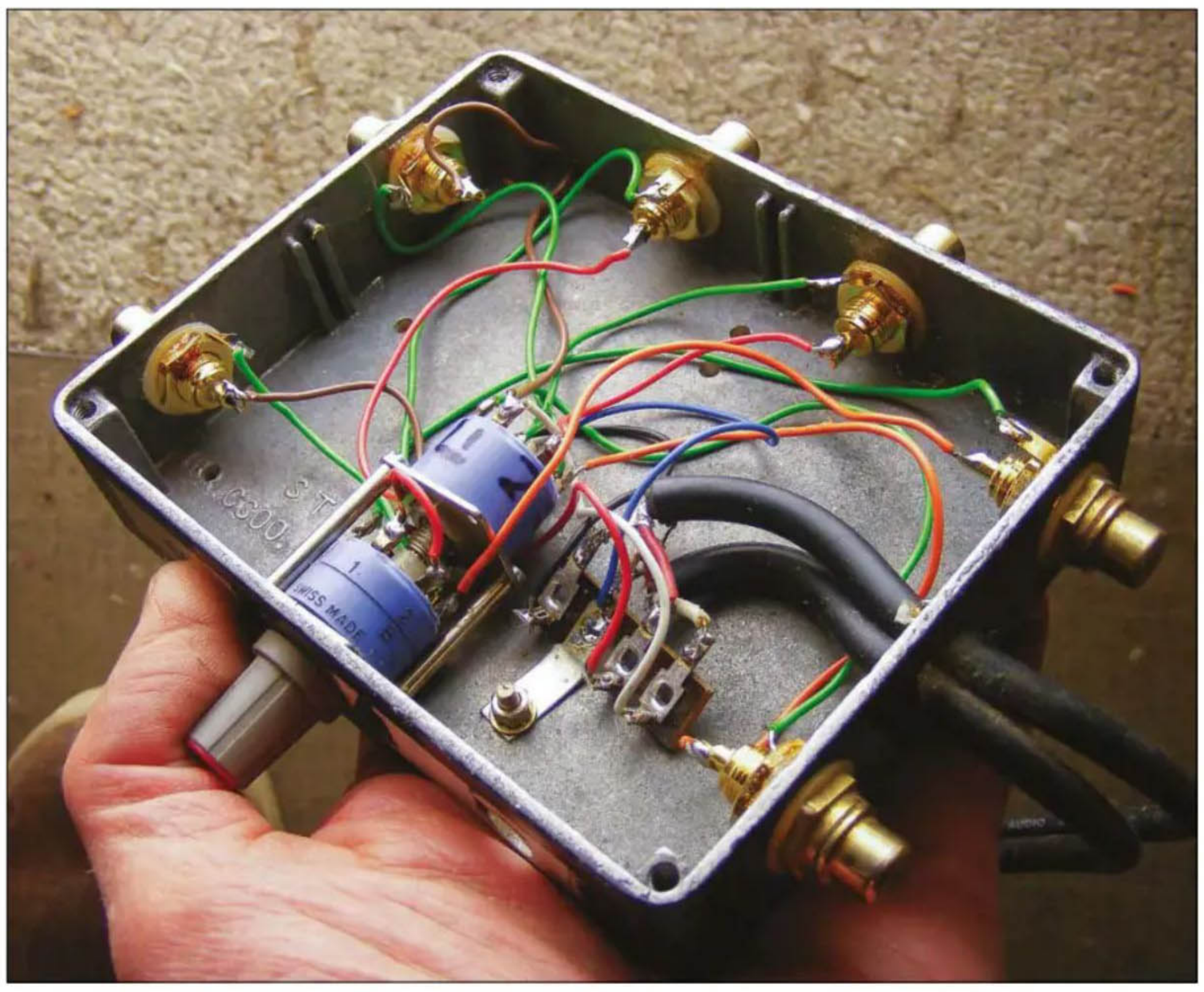

Fig.25. A dedicated three-position source selector switch with earth switching using an expensive 02 series Elma rotary switch.

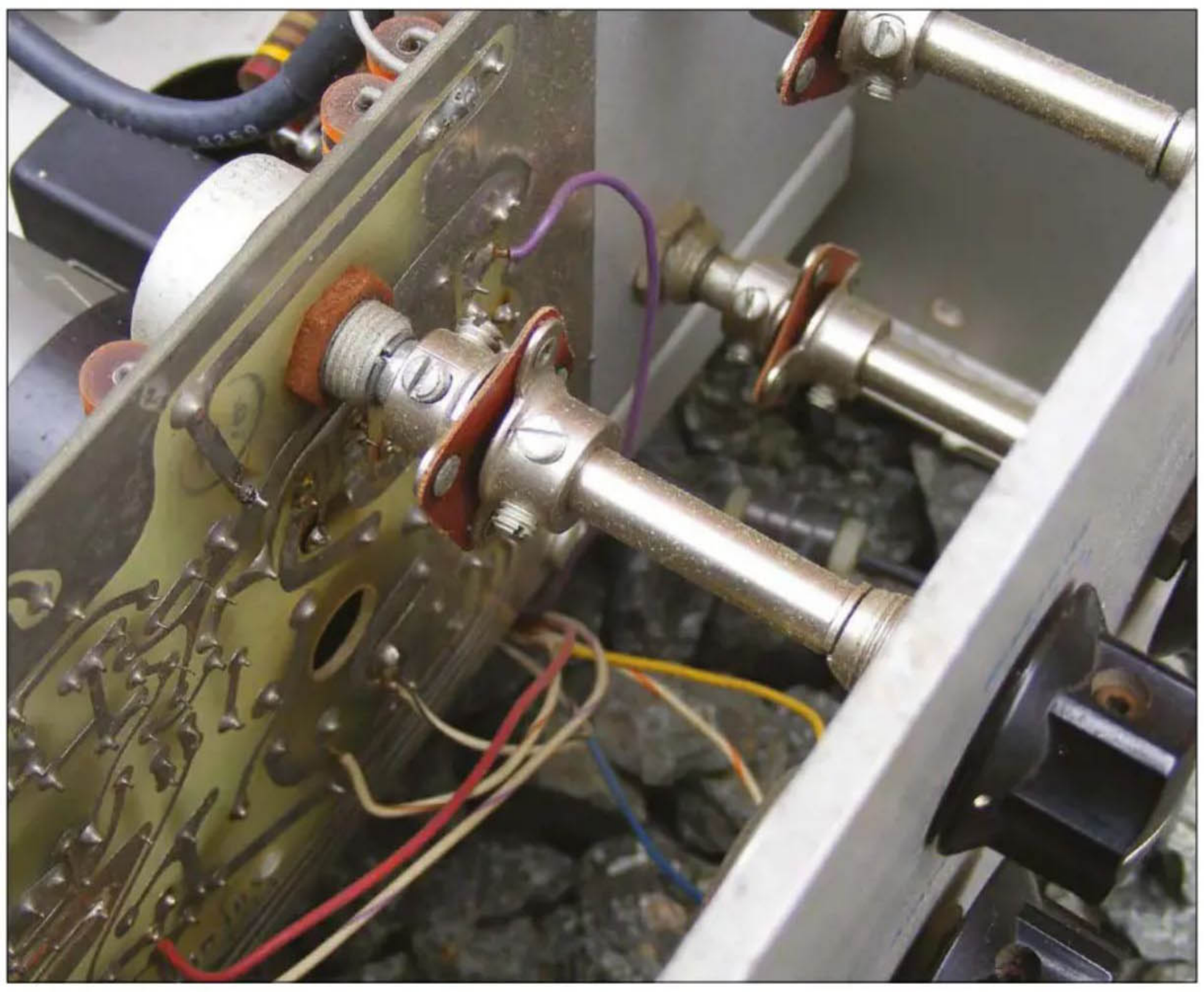

Fig.27. An extension spindle enables a switch to be placed in an electrically quiet area. In this case a flexible coupling has been used to decouple vibrations.

to a quiet radio signal (say, classical music on BBC Radio 3), and having inadvertently left the CD player going, one can hear a faint frequency from the CD player in the background. (Hi hat cymbals seem to bleed through especially well.) This inadvertent coupling is due to the capacitance between the contacts and cables. It gets worse if the source impedance of the selected source is high – in the case of some FM tuners and valve pre-amps this may be up to 10kΩ. The capacitance effectively makes a high-pass filter with this resistance, so if it is high the coupling frequency is lower hence the hi hat being especially noticeable. Crosstalk is specified in the same way as signal-to-noise ratio, in decibels (–dB) below the signal. This figure is given at a high frequency, say 20kHz, and can be in the order of –70dB, improving to –120dB in the best cases.

By screening the cables and using buffers with a low output impedance the crosstalk can be greatly reduced, as shown in Fig.26. Another popular dodge is to put a rotary switch on the back panel next to the input sockets. This switch is then mechanically coupled to the knob at the front using an extension spindle and brackets – see Fig. 27. This approach also minimises hum and noise and is popular in expensive integrated (combined pre- and power) amplifiers. It requires care with mounting to the front panel bushing to prevent play and a floppy feel. I use a viscous damping grease such as Kilopoise and a felt washer under the knob. Shaft extensions were used in T Giesberts *Mini-preamplifier* (*Elektor*, February 1994).

To prevent crosstalk there are several other effective techniques. Rotary switches sometimes include a metal screen between the two sections, as shown in Fig.28. On PCBs it is always worth putting earthed guard tracks between the input lines going to the switch, along with a ground plane to mimic screened cables. Another trick is to ground the unused sources. Care has to be taken to ensure this does not cause any damage to the source though. Normally a series resistor of around 600Ω prevents excessive current. However, there can still be the problem of preventing current going to ground which can cause resistive crosstalk. This can be alleviated by connecting the ground to a low impedance point, such as the power supply. In the days of the Maka-Switch one could buy a 'rotating open-circuit' wafer, as shown in Fig.29. By linking across to an adjacent normal wafer, all the unused sources were automatically grounded. It's also possible to do the

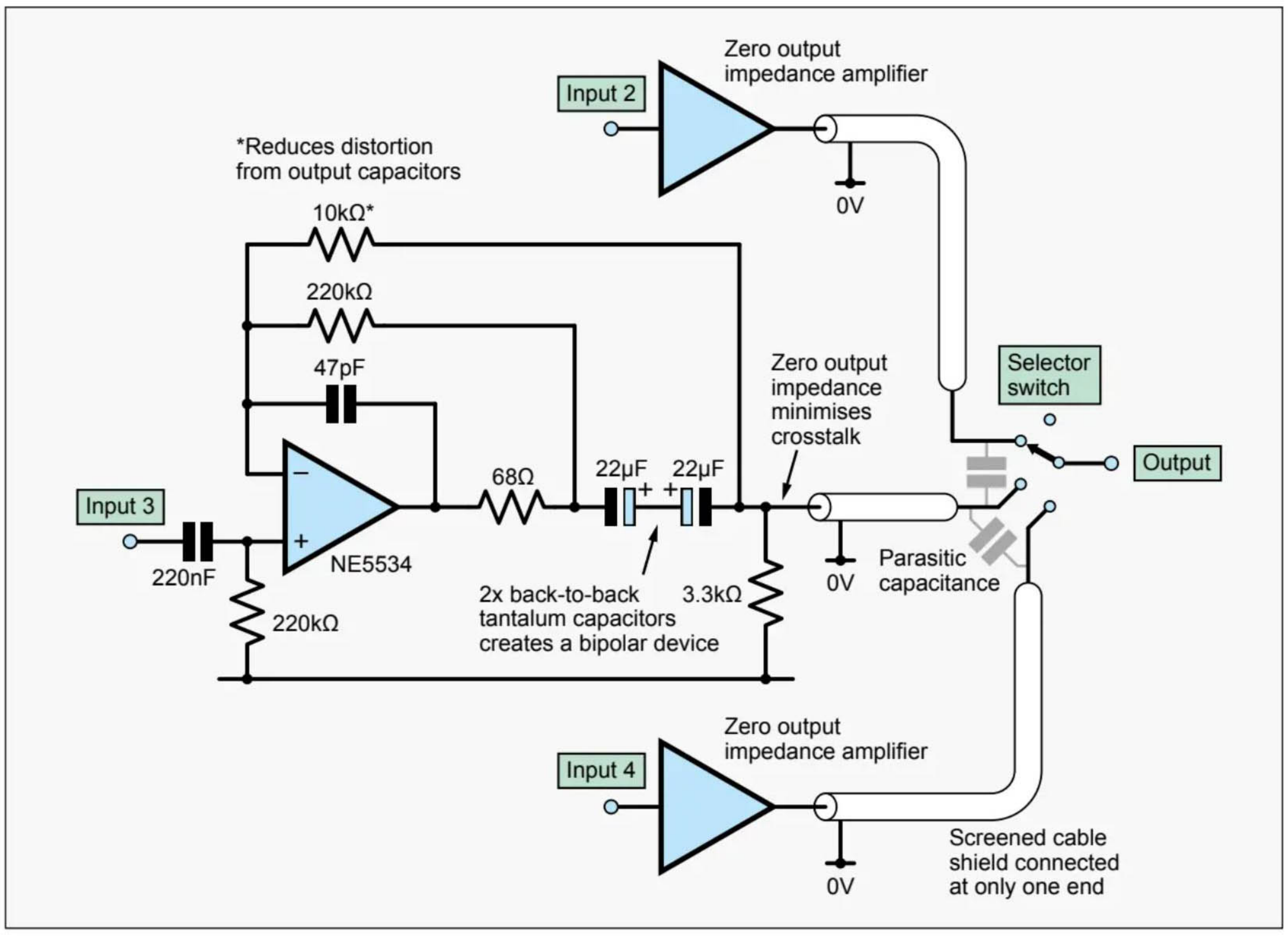
Input 2
Zero output impedance amplifier
0V
*Reduces distortion from output capacitors
10kΩ*
220kΩ
47pF
Zero output impedance minimises crosstalk
Selector switch
Output
Input 3
220nF
NE5534
68Ω
22µF
22µF
220kΩ
2x back-to-back tantalum capacitors creates a bipolar device
3.3kΩ
0V
Parasitic capacitance
Input 4
Zero output impedance amplifier
0V
Screened cable shield connected at only one end

Fig.26. Feeding switches from low impedance sources, such as zero-output impedance buffers, reduces crosstalk between switching elements and cables.

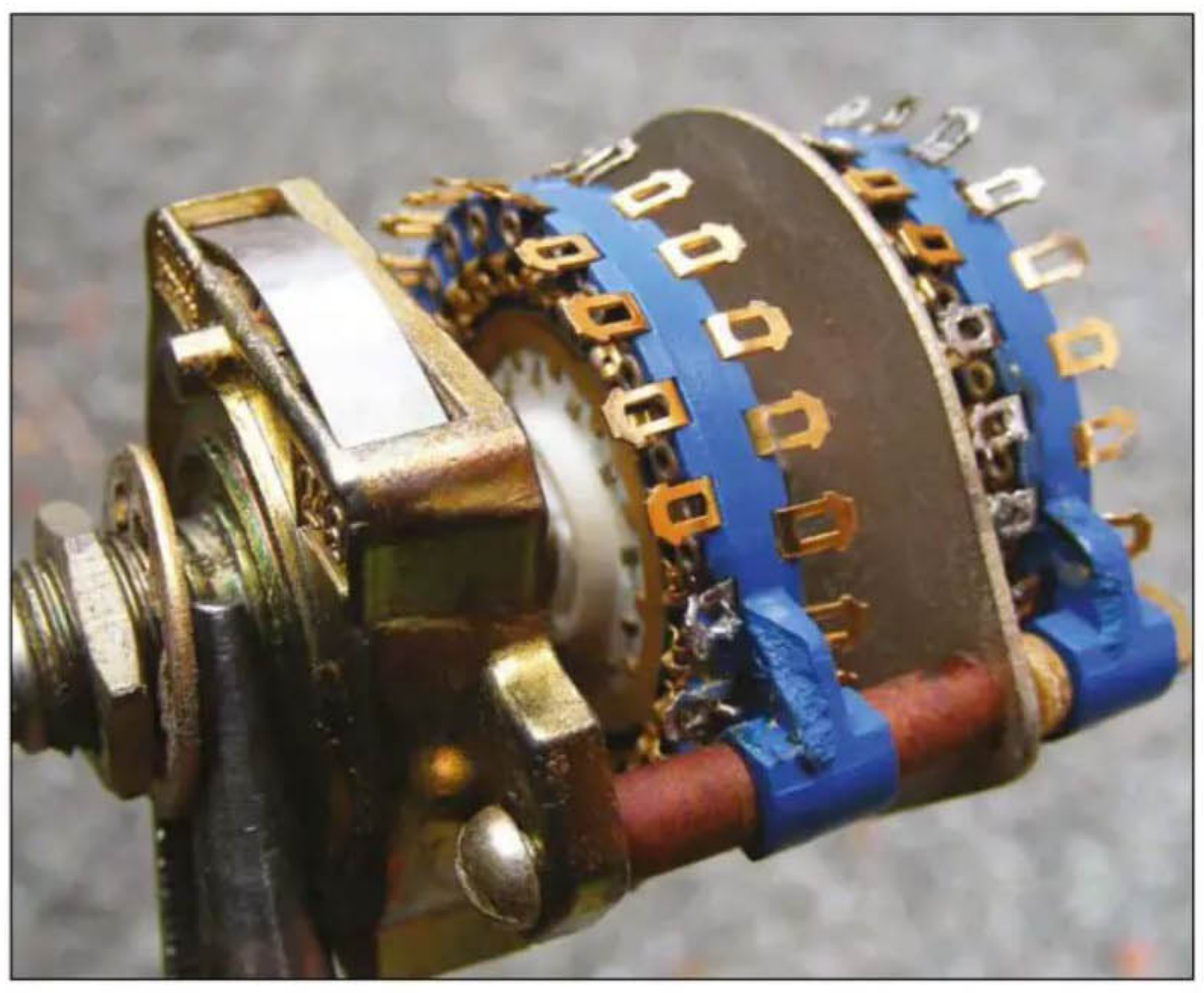

Fig.28. An earthed metal screening plate can be placed between two switch sections to reduce coupling. Useful for preventing crosstalk between left and right channels.

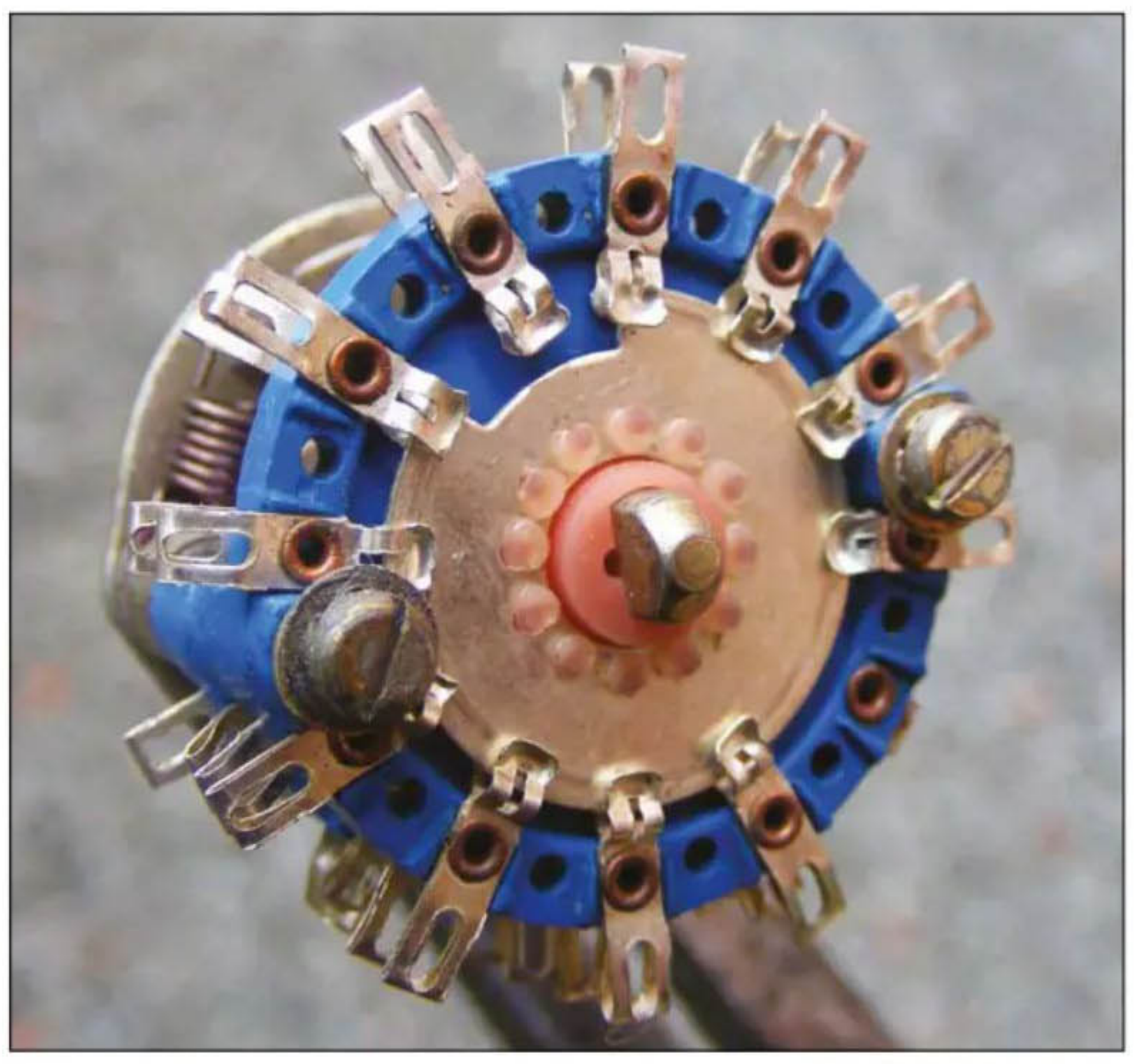

Fig.29. A 'rotating open-circuit' wafer. This can be used to ground all contacts except the position selected.

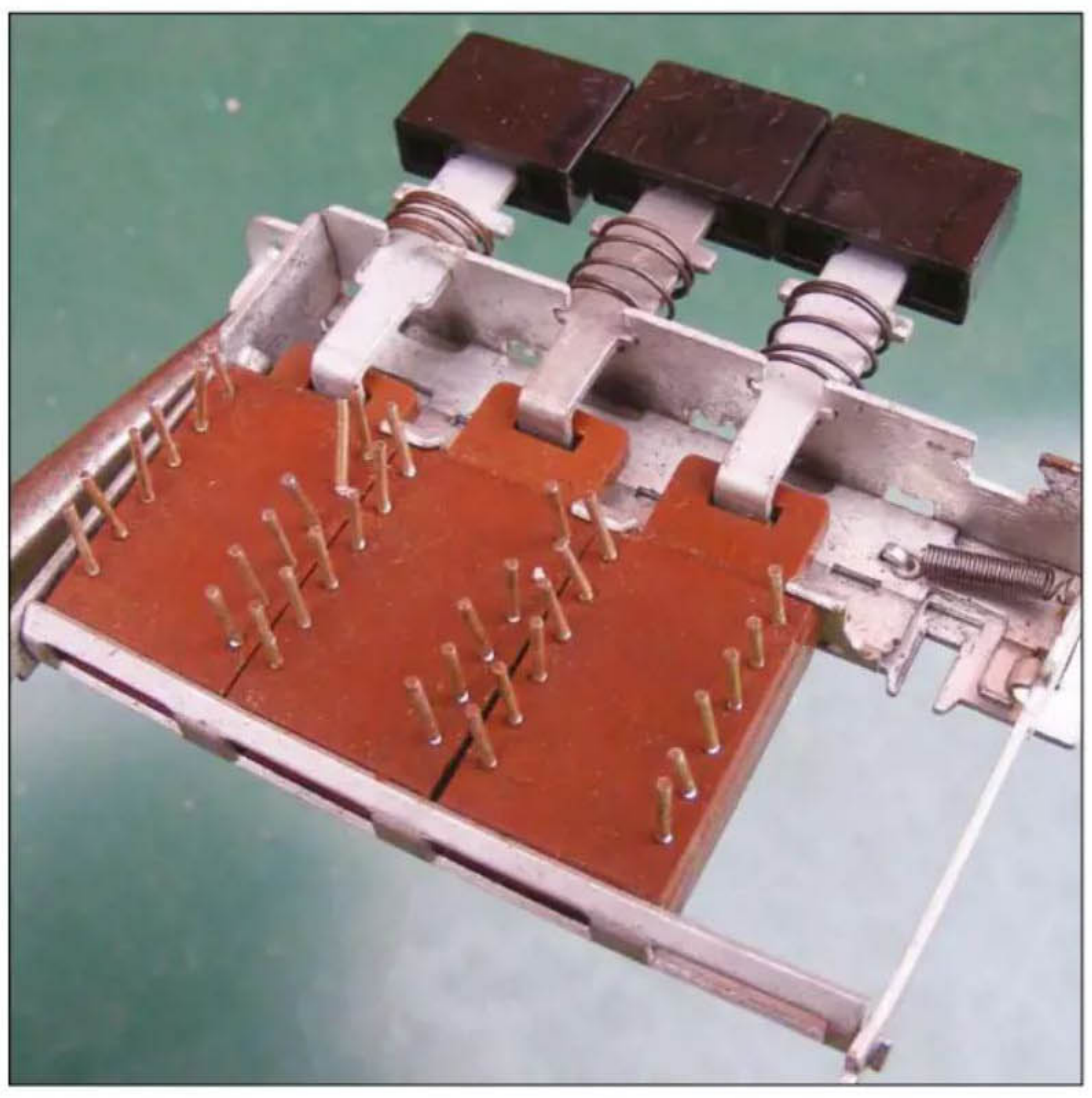

Fig.30. Mechanically interlocked push buttons. Notice the spring.

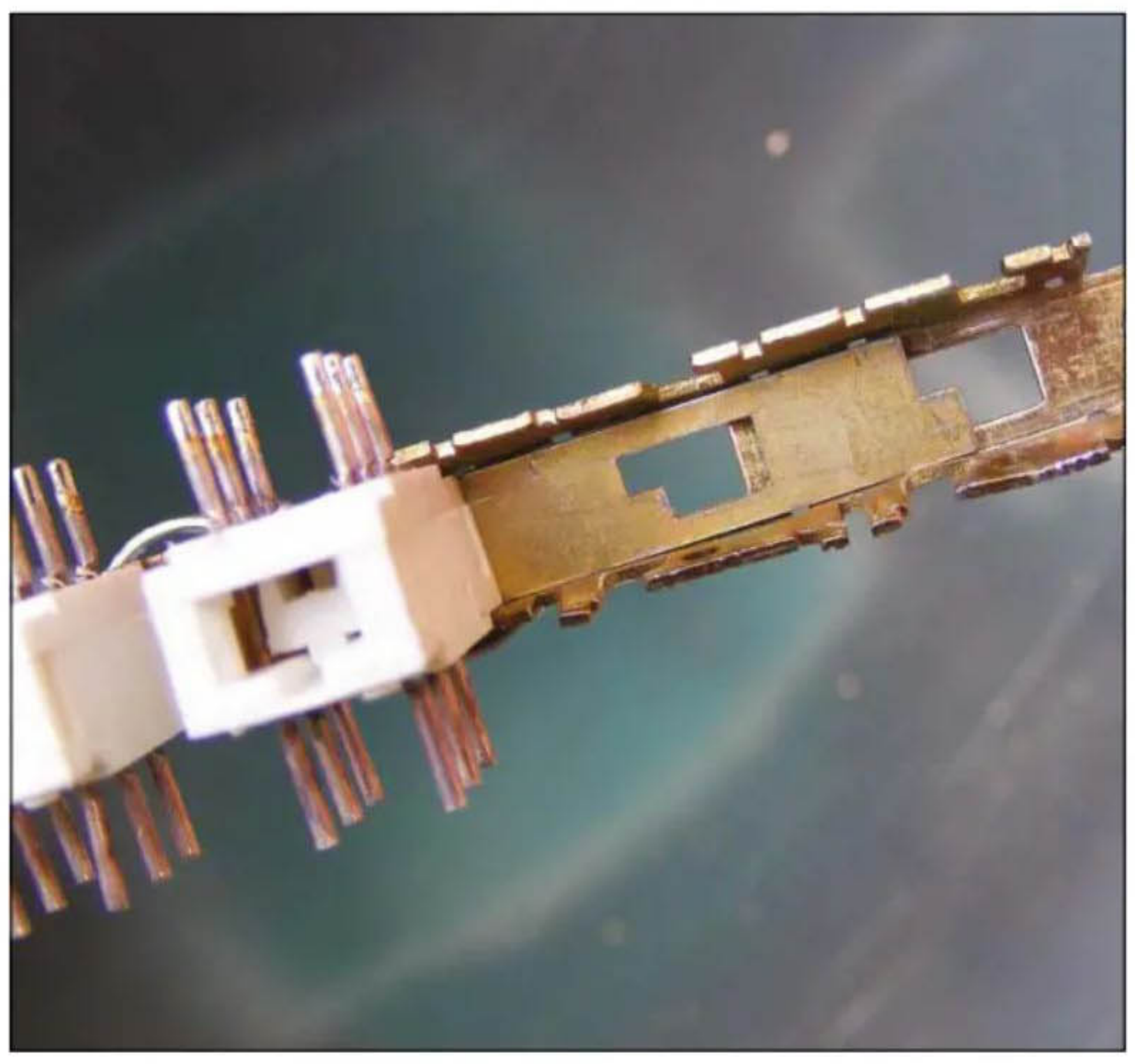

Fig.31. Interlocking is accomplished by a spring-tensioned sliding bar with latching tabs underneath all switches.

same thing with interlocking push buttons, as in Douglas Self's preamplifier (*Wireless World*, September 1996).

Multiple push buttons

An alternative to the rotary switch is an interlocking push button, where only one button can be on (in) while the others are always off (sticking out) as illustrated in Fig.30. These are often easier to operate and offer the possibility of clearer labelling. They were popularised by German industrial designers such as Dieter Rams of Braun with his 1959 SK4 radiogram. Indeed, they are replicated on computers screens today in graphical user interface (GUI) software as 'radio buttons'. Mechanical interlocking has a sliding bar interlinking all the switches (see Fig.31). Such assemblies are prone to go wrong and it's often impossible to get a replacement. There was one design of button that incorporated a black 'eyelid' which opened to reveal a florescent orange disc when pressed – see Fig.32. Most designers today would go for an electronic interlocking system with LEDs which, unlike the 'eyelid', requires power.

Post Office/BBC switches

I mention these because they often turn up in old BBC equipment, and are sometimes called 'lever switches'. They are very reliable, achieving a million operations. They have an open construction with easy-to-clean multi-contacts, as shown in Fig.33. They also make no mechanical noise, but on the downside they are expensive, and mounting them is awkward. They need a rectangular hole and two screw holes with precise relative dimensions.

Funny shapes, odd holes

For small-scale constructors, switches that are fastened with a nut in a round hole are the most convenient, such as toggle and rotary types. They also allow the front panel to be completely sealed, unlike rows of interlocking push buttons. In general, I try to avoid switches that require rectangular holes which either need an expensive cut-out punch or fiddly, time-consuming sawing and filing. This precludes a lot of rocker and some push switches – the kind shown in Fig.34. I have even had 3D-printed adaptor plates made for some push buttons – see Fig.35. Of course, for medium-scale production I outsource the front panels and then the rectangular switches just clip in. (Getting them out again for replacement/maintenance though is another matter!)

Soldering meltdown

Some cheap switches use thermoplastic cases rather than the old Bakelite thermosetting material. Take care with these when soldering. If the wire is pulled while it is still hot, the tag/contact

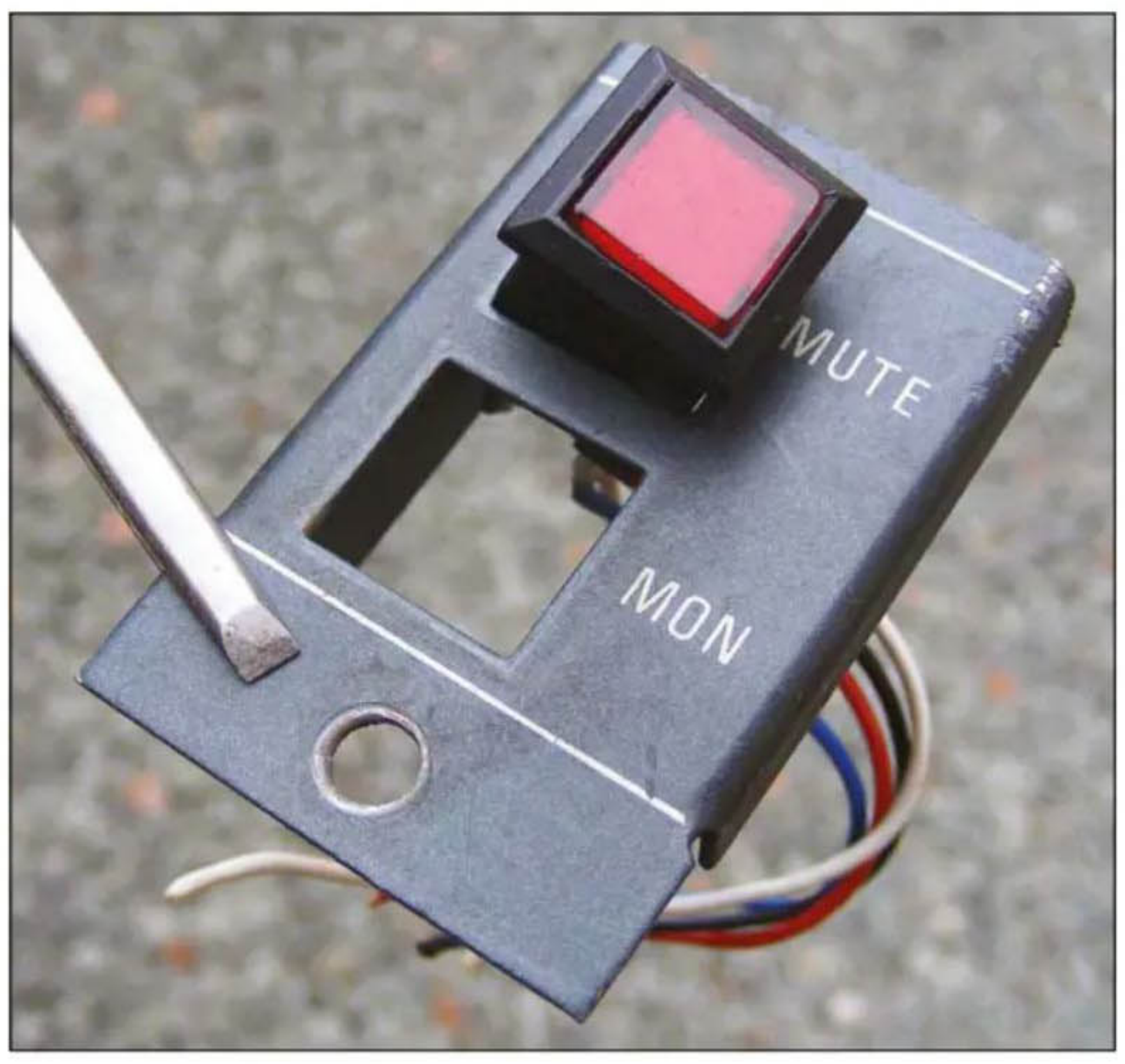

Fig.34. These lovely LED illuminated Japanese push buttons require a difficult-to-cut hole.

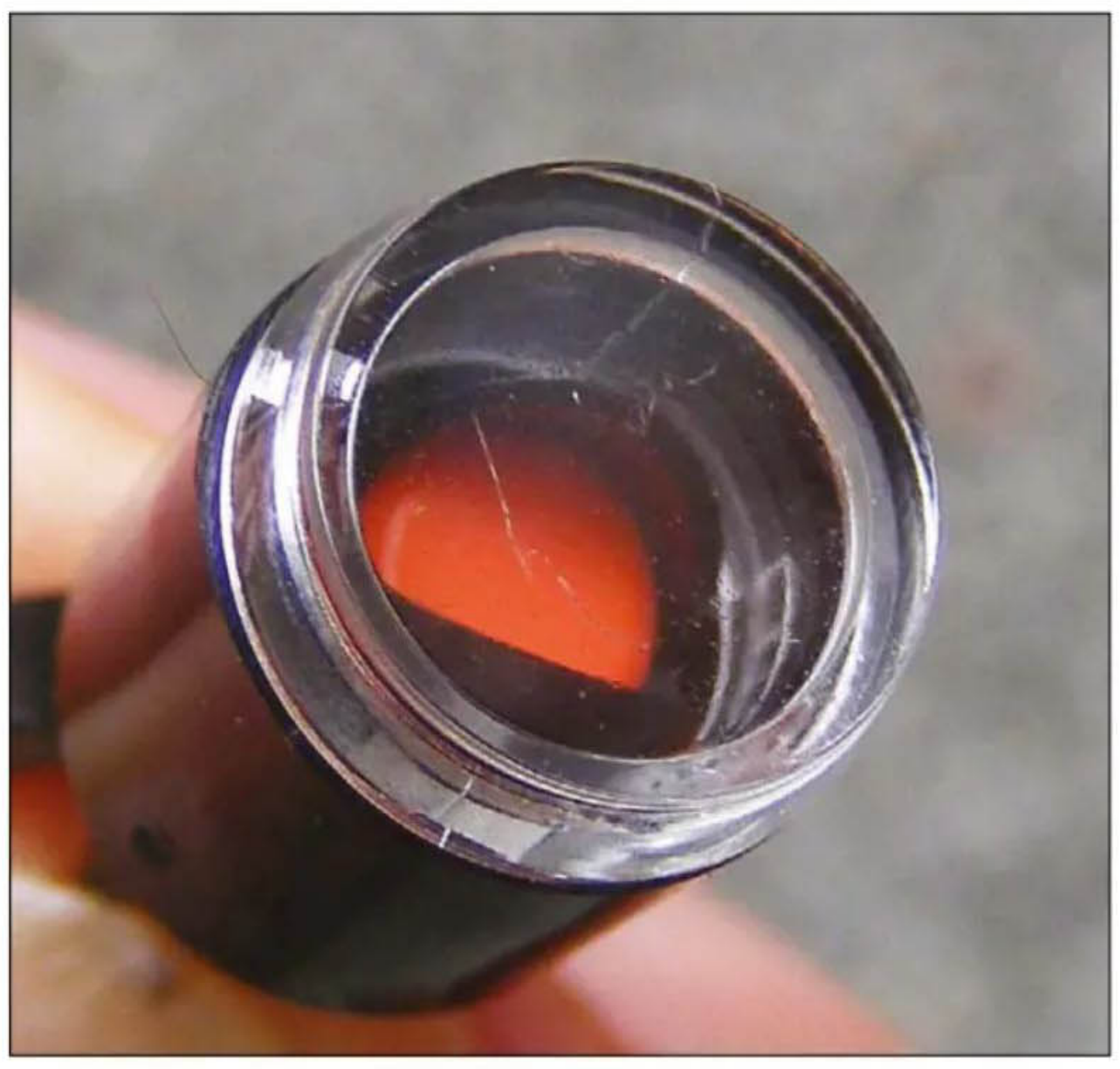

Fig.32. An interesting push button by Schadow that uses internal 'eyelids' to reveal a fluorescent 'on' indicator when the actuator is pressed.

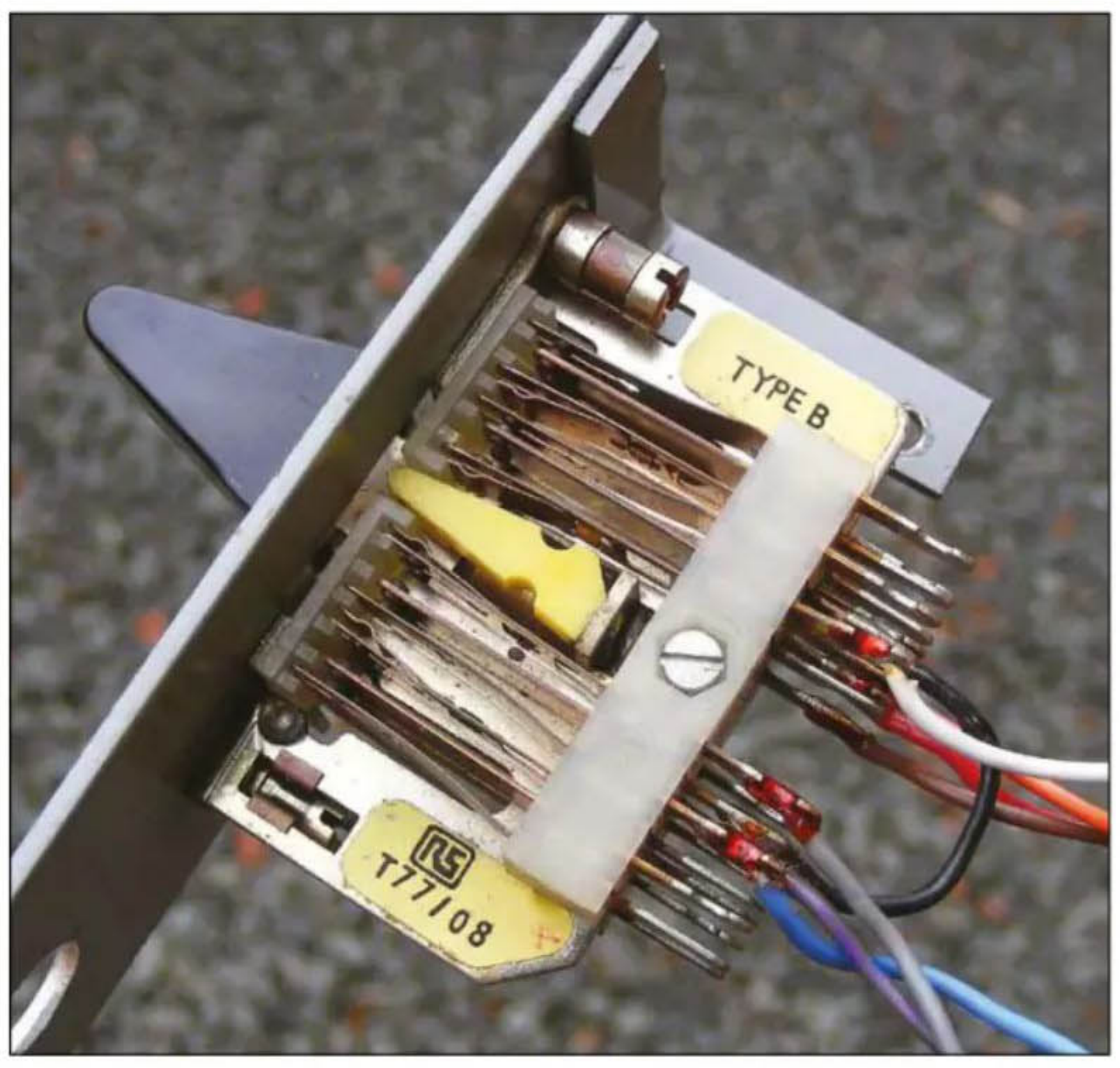

Fig.33. Old-fashioned Post Office switches used by the BBC were very reliable and you could get them in almost any combination.

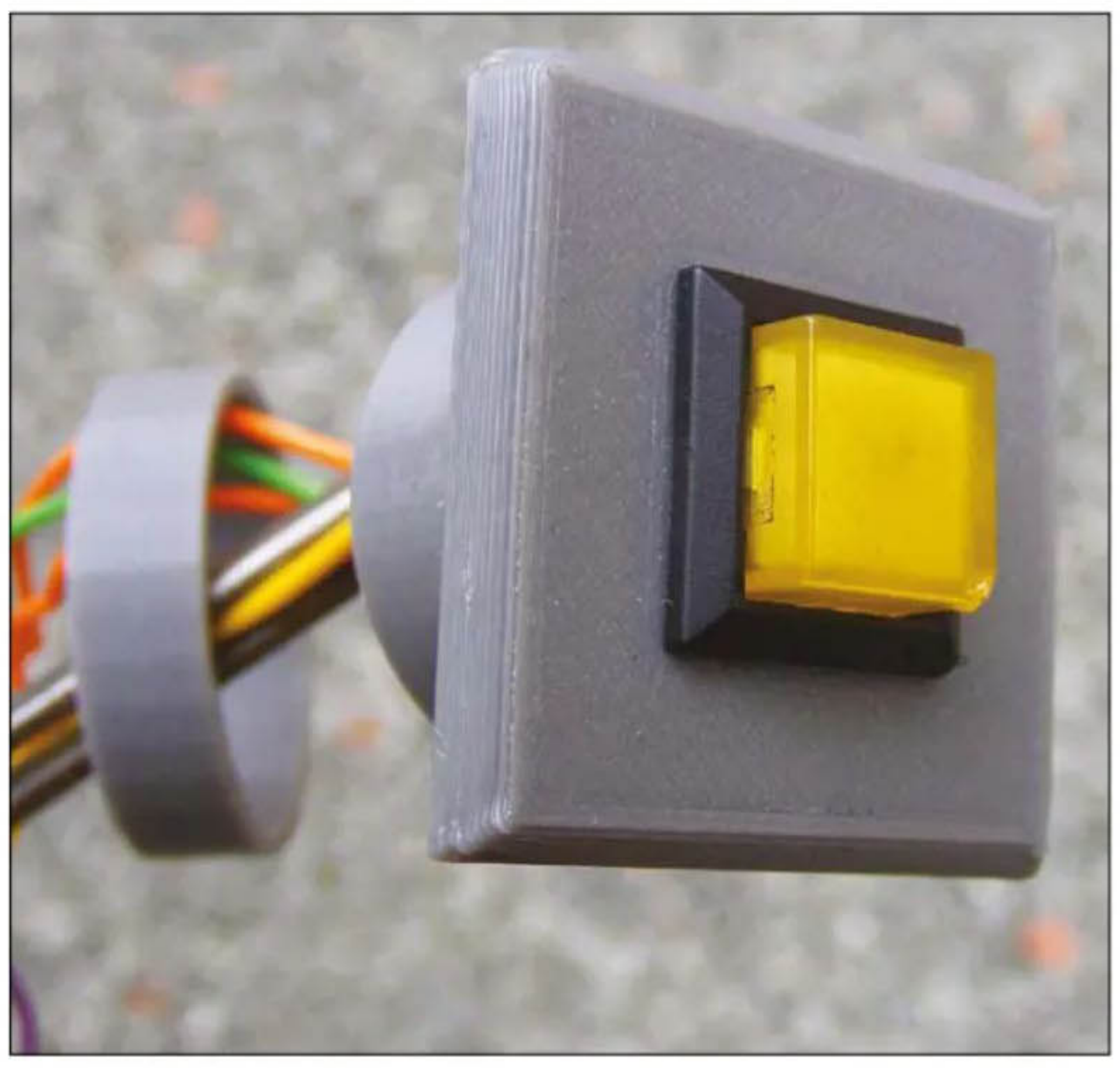

Fig.35. A square switch in a round hole. An adaptor plate for the switch type shown in Fig.34. A 3D print designed by my friend, Jeremy Paine.

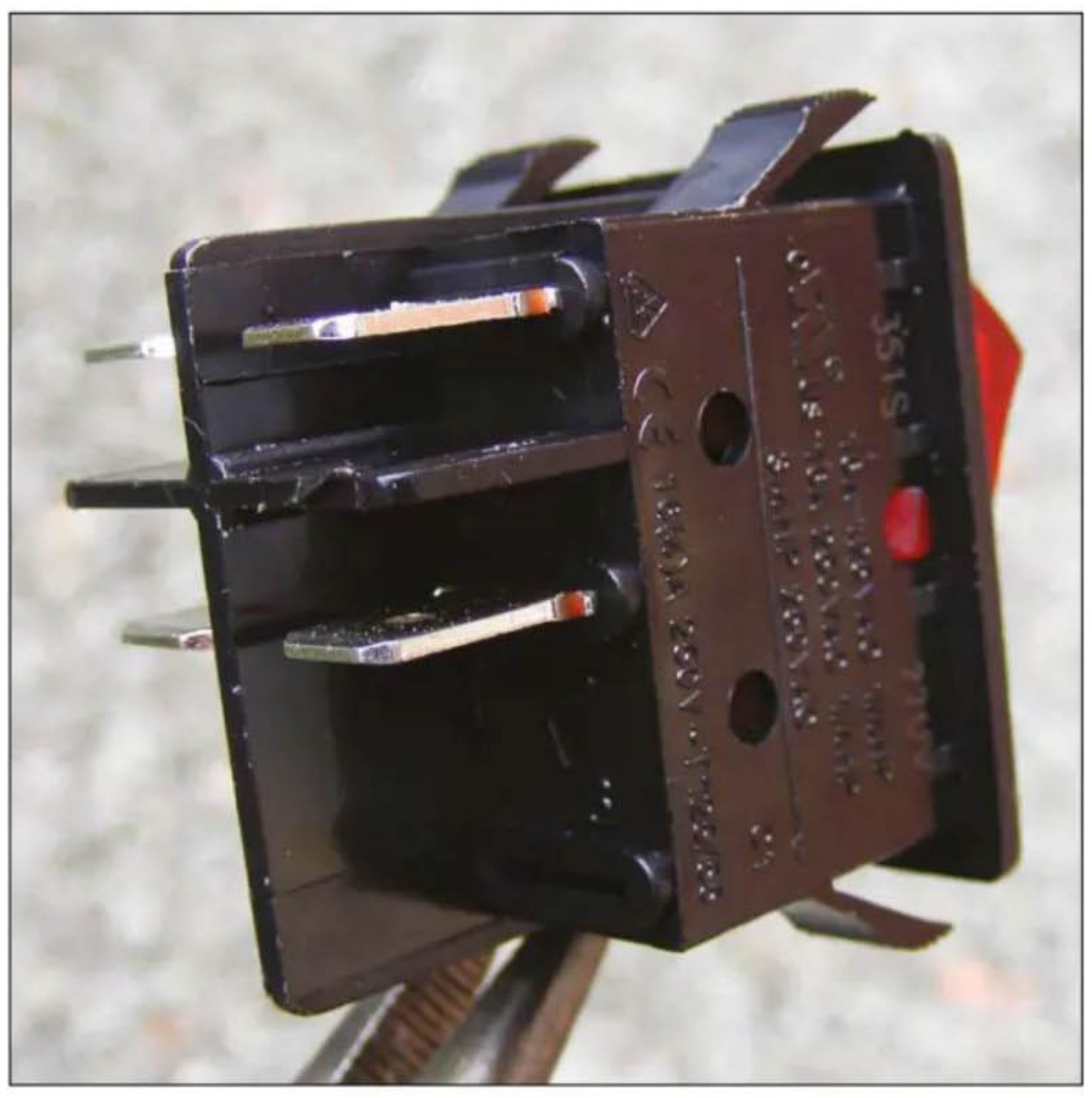

Fig.36. Once you get the front panel rectangular hole right, the switch just clips in with the plastic tabs. This is a typical rocker mains switch. A pig to get out though, since all the tabs have to be squeezed in together. Note these switches melt and can fail when soldered. They are designed for push-on insulated spade connectors.

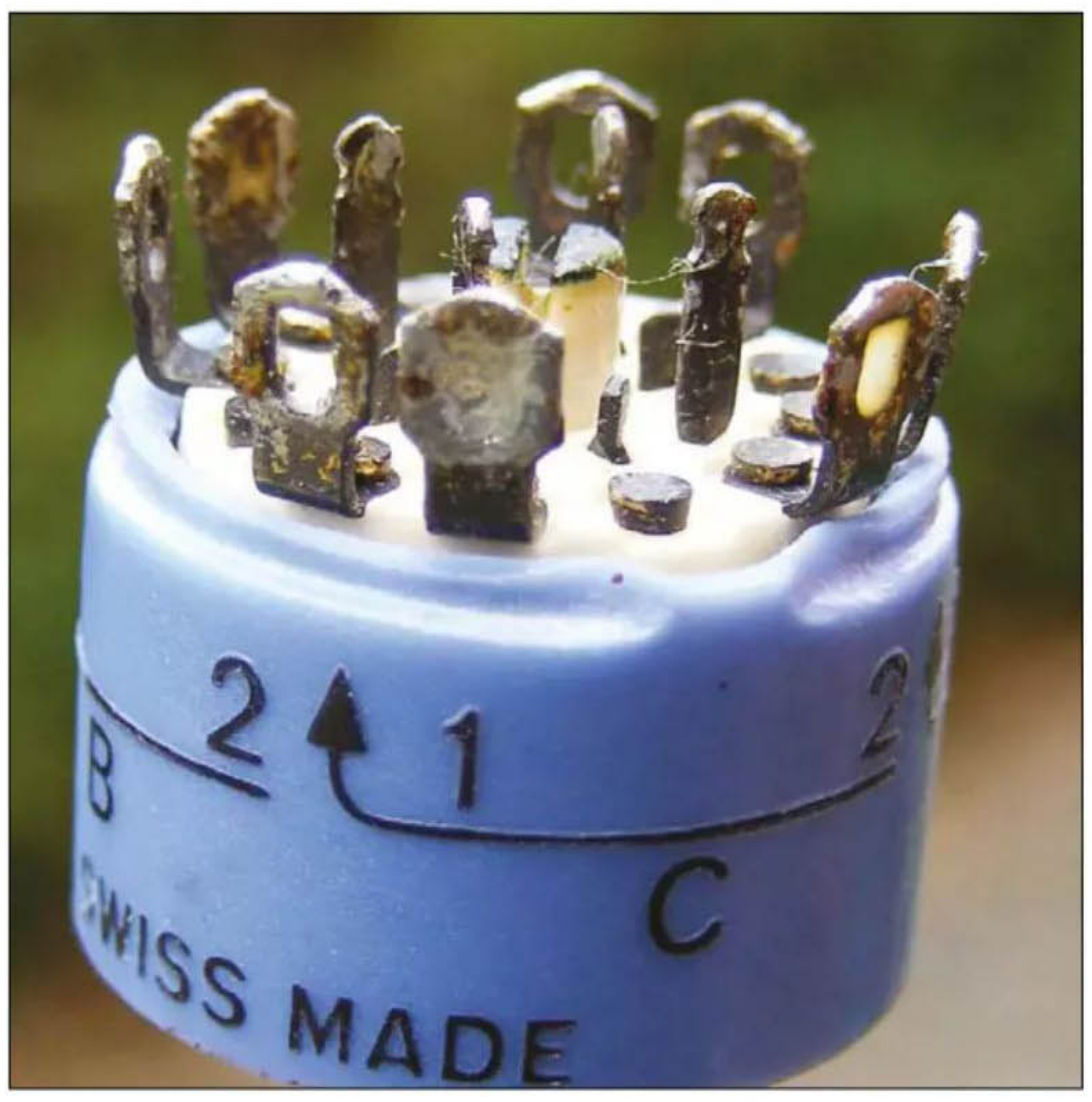

Fig.37. Black sulphide tarnish on switch tags can be impossible to solder. However, in this situation the switch surprisingly usually still works.

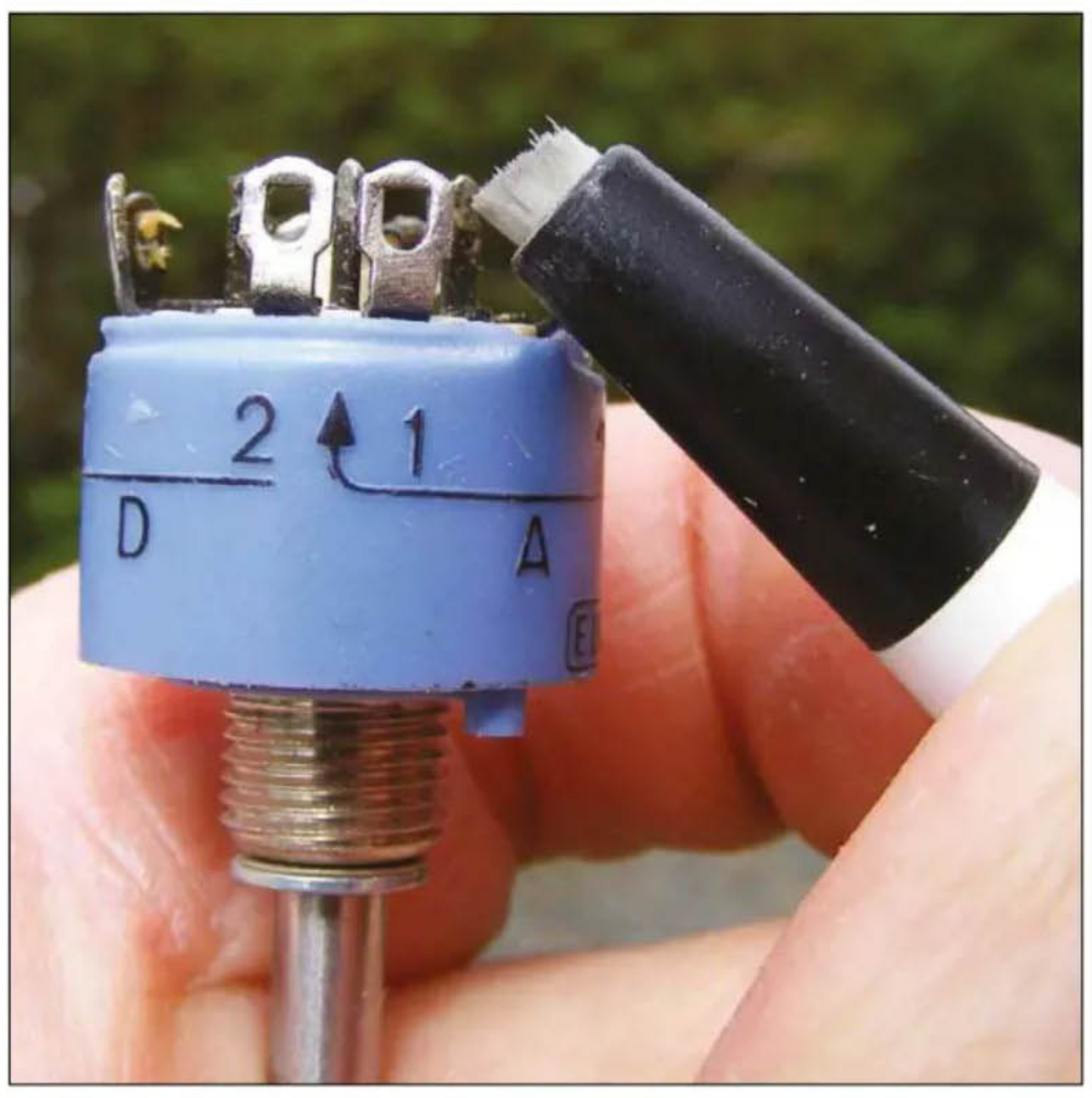

Fig.38. A glass fibre brush is the best way to clean contacts.

can move as the plastic softens, resulting in an open circuit. This also happens with mains rocker switches (Fig.36). They are designed for push-on tags, not soldering. Don't clean solder flux off switch tags, the solvent can wash the flux into the switch contacts where it dries like a varnish causing an open circuit. The black silver tarnish that often occurs with switches (Fig.37) can often make the tags impossible to solder, even though the switch often works fine with enough current. The solution is to use a glass fibre brush to clean them – the type shown in Fig.38.

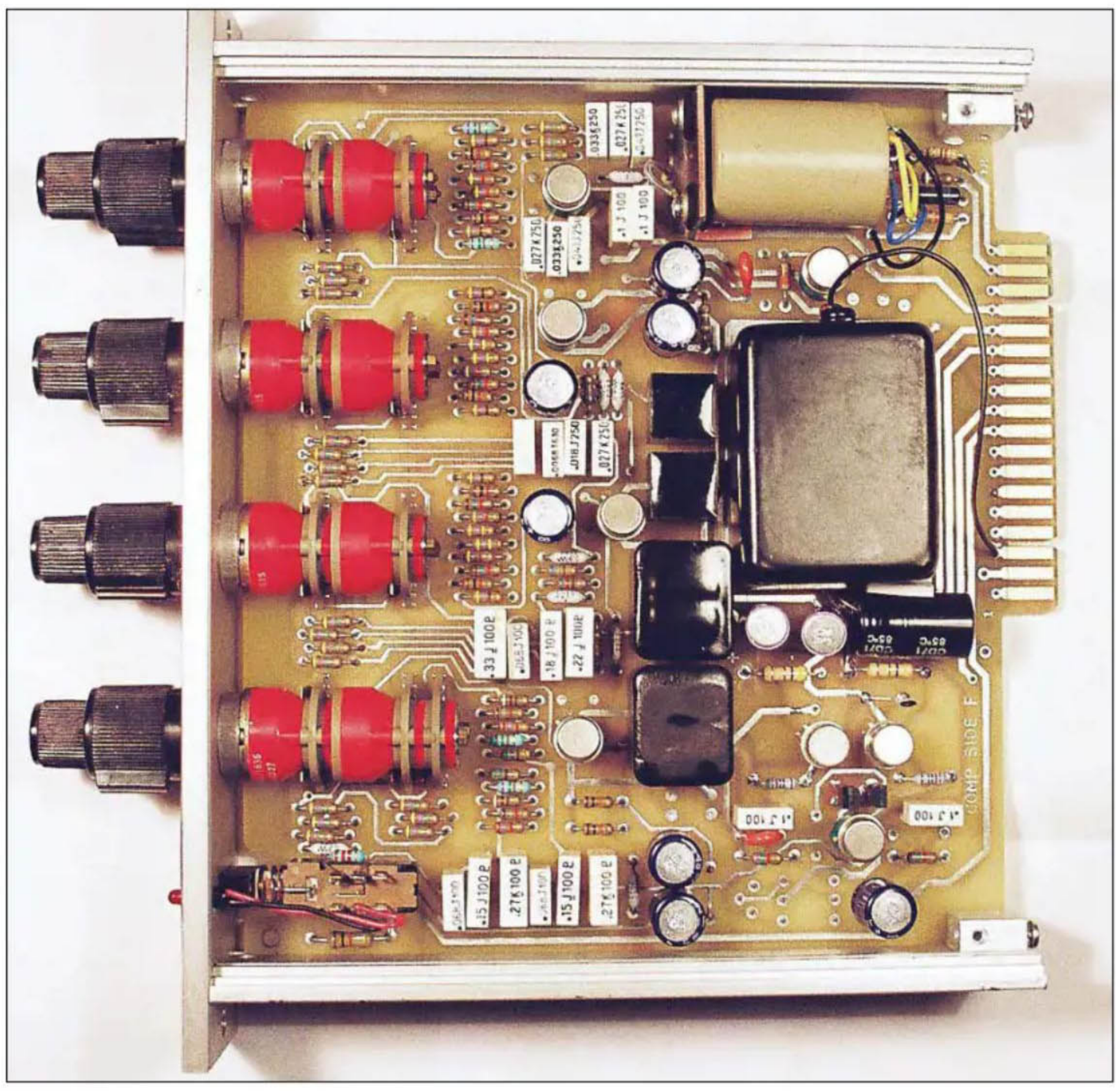

Fig.39. Here's some multi-gang PCB mount rotary switches on an equaliser module. Last time I bought one of these Greyhill switches it cost £35.

PCB mounting

I used to avoid PCB-mounted switches since the high mechanical forces imparted on the board gave rise to dry joints. This is much less of a problem today because of plated-through holes. For maintenance work there is still the problem of finding switches to fit a PCB layout since an exact physical replacement is always required. Fig.39 shows an API-inspired audio equaliser with rotary Greyhill switches connected to resistor ladders giving precise dB control steps. It is possible to get a complex multi-pushbutton assembly made up (see Fig.40) which is soldered into the PCB as one unit. The goal is to eliminate a stack of wiring and possible errors – assuming you get the PCB layout right! These set-ups are common in Hi-Fi pre-amps and audio test sets such as the Wayne Kerr AMS1 audio analyser shown in Fig.41 and 42.

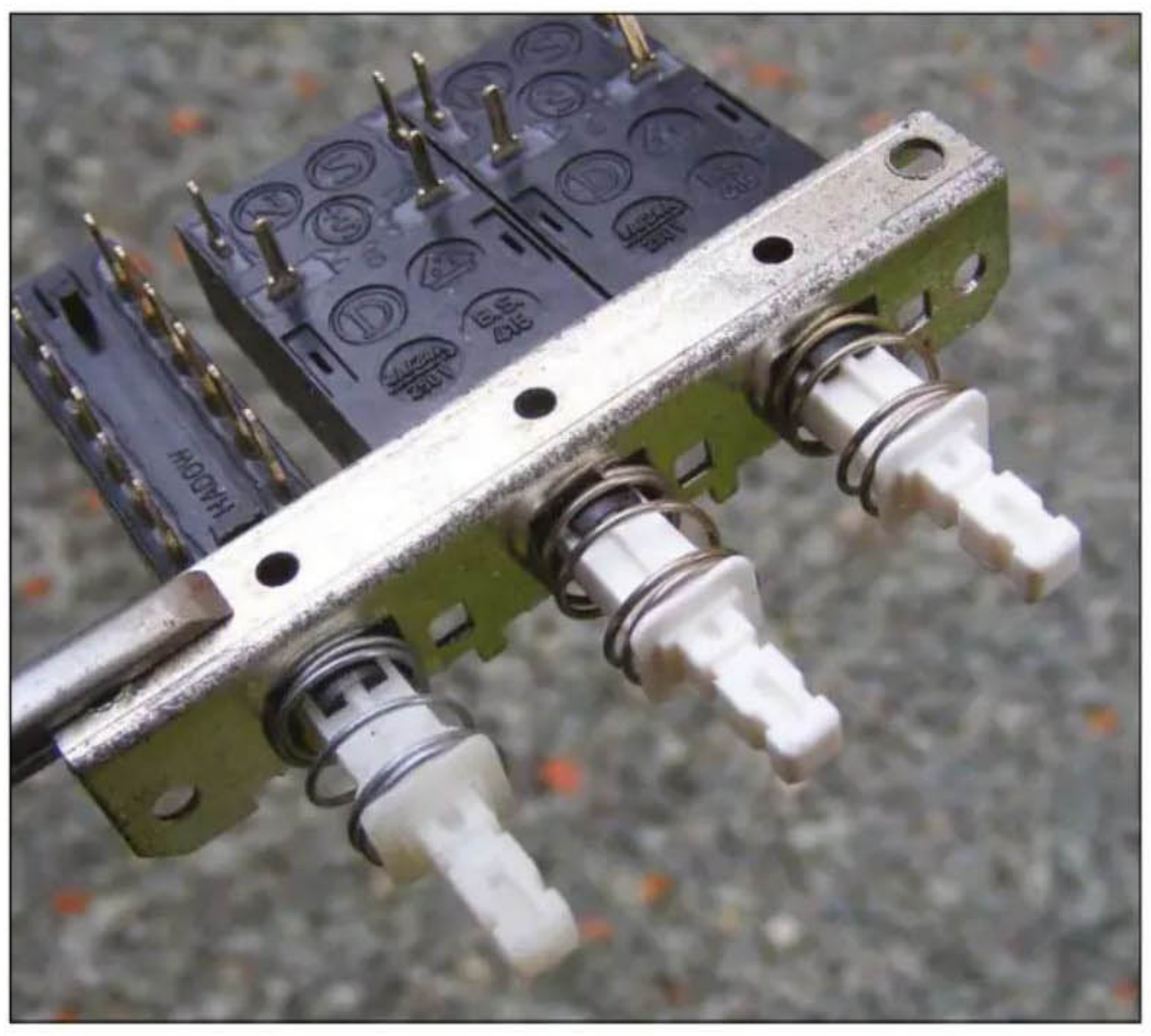

Fig.40. A custom-made push-button assembly ready to solder into a PCB. This has two high-current switches for speakers and a small-signal DPDT switch.

Switch odyssey

One of the switches failed in my Wayne Kerr AMS1, by shooting out of the front panel across the room. It's contacts and other small parts were scattered in the process, most of which were never found. Unfortunately, it was the most important button on the front panel; in this case, the 1kHz test signal switch. It took a year for me to find a replacement for these white switches – they turned up quite by chance at a radio rally. Then it took half a day of microsurgery to fix it. All that hassle because of a plastic-tab failure on the end of the internal plastic slider (Fig.43). I inserted a cropped Veropin in a 1mm hole drilled where the missing

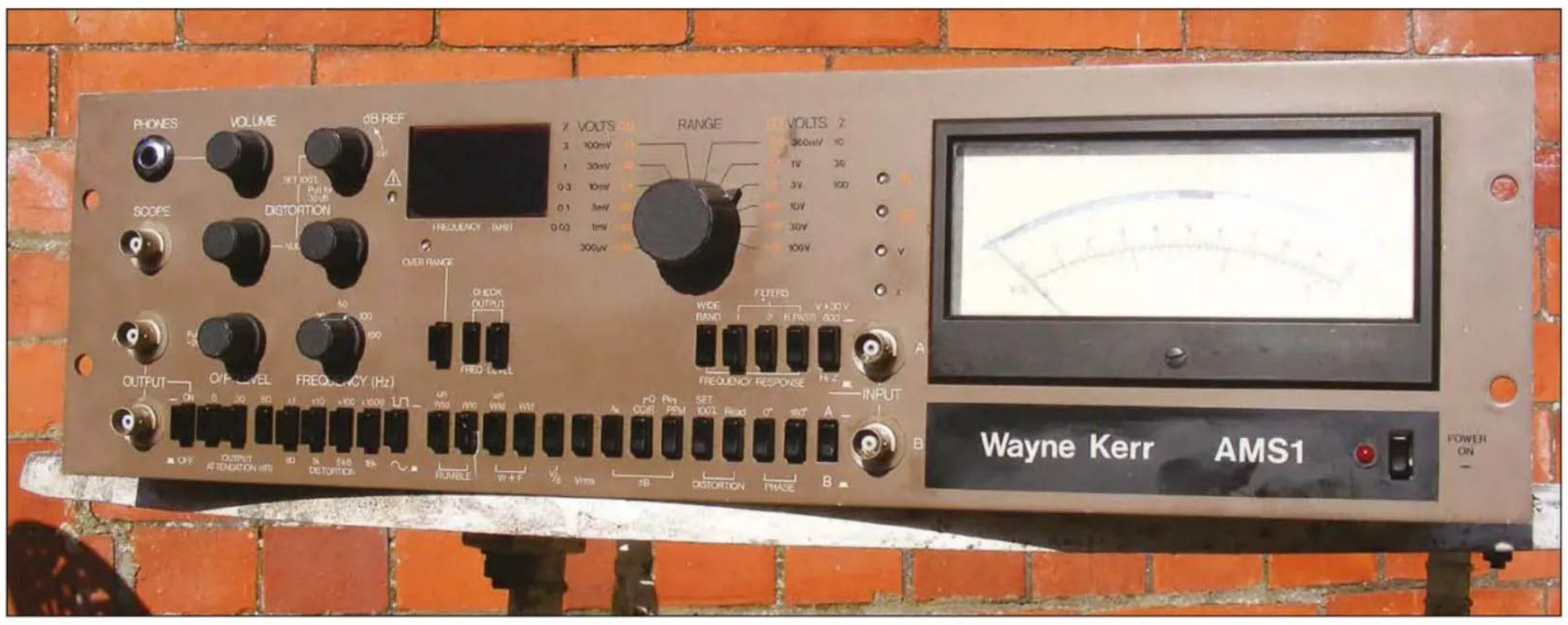

Fig.41. A complex PCB-mounted interlocked push button assembly on the AMS1 audio analyser front panel. Switch problems in systems built like this are a nightmare to fix.

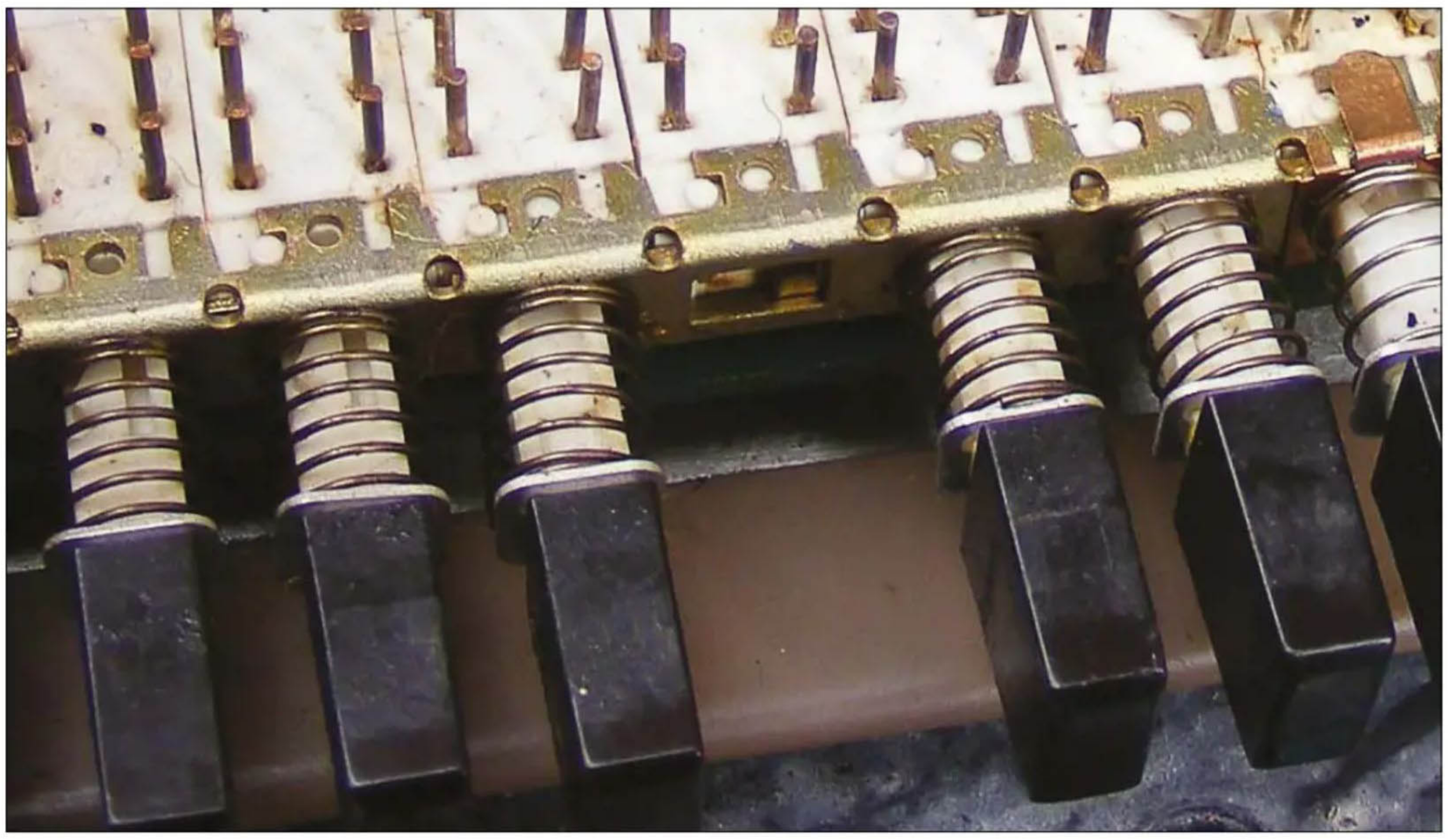

Fig.42. Interior of my AMS1. The Centralab switches are white and mounted on the lower PCB. The latching spring and contacts went missing, and they weren't in the Hoover bag.

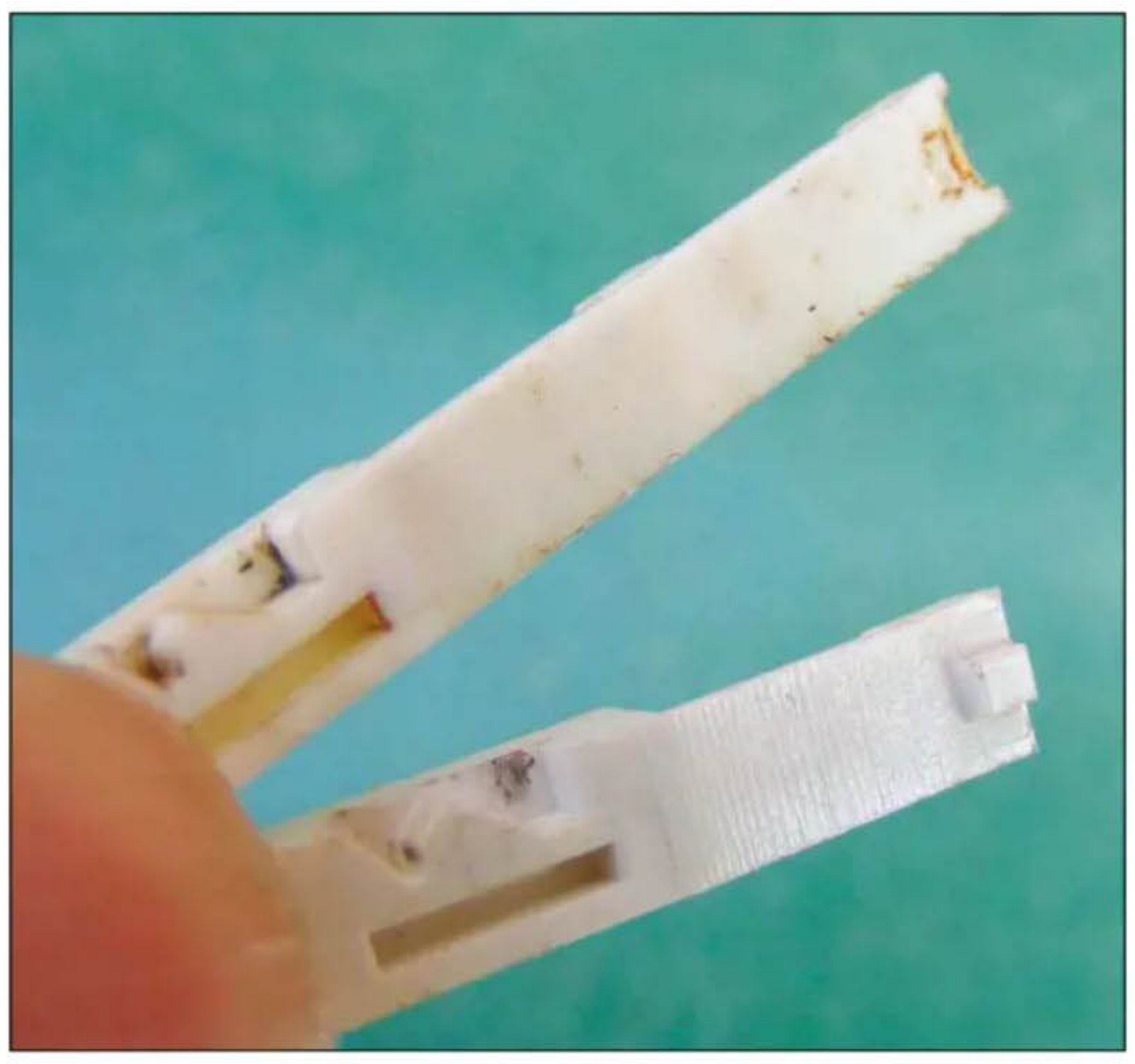

Fig.43. The bane of my life, the plastic tab failure. This little bit of plastic breaking off the (upper) internal switch slider resulted in half a day's work.

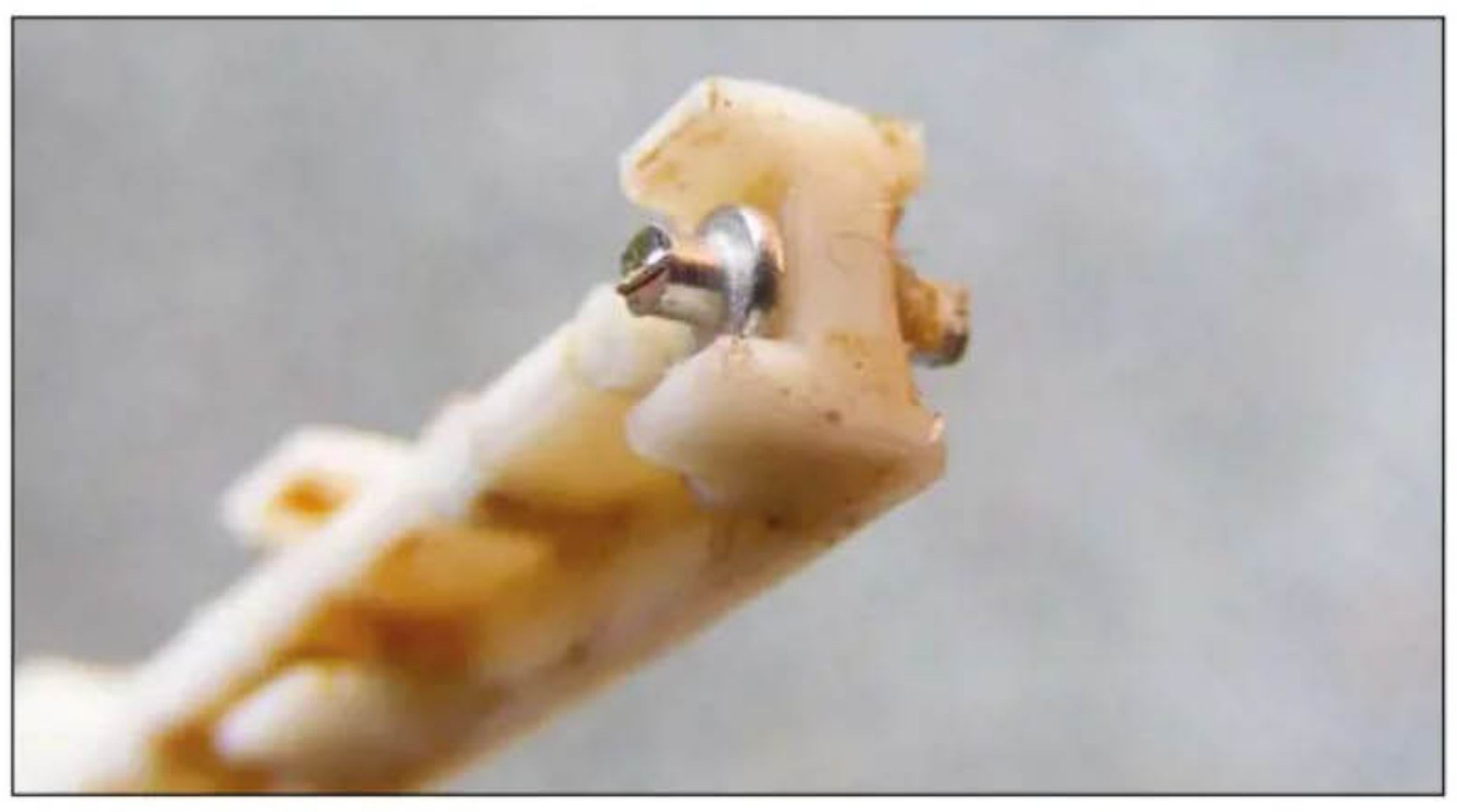

Fig.44. The plastic tab was replaced by inserting a truncated Veropin in its place.

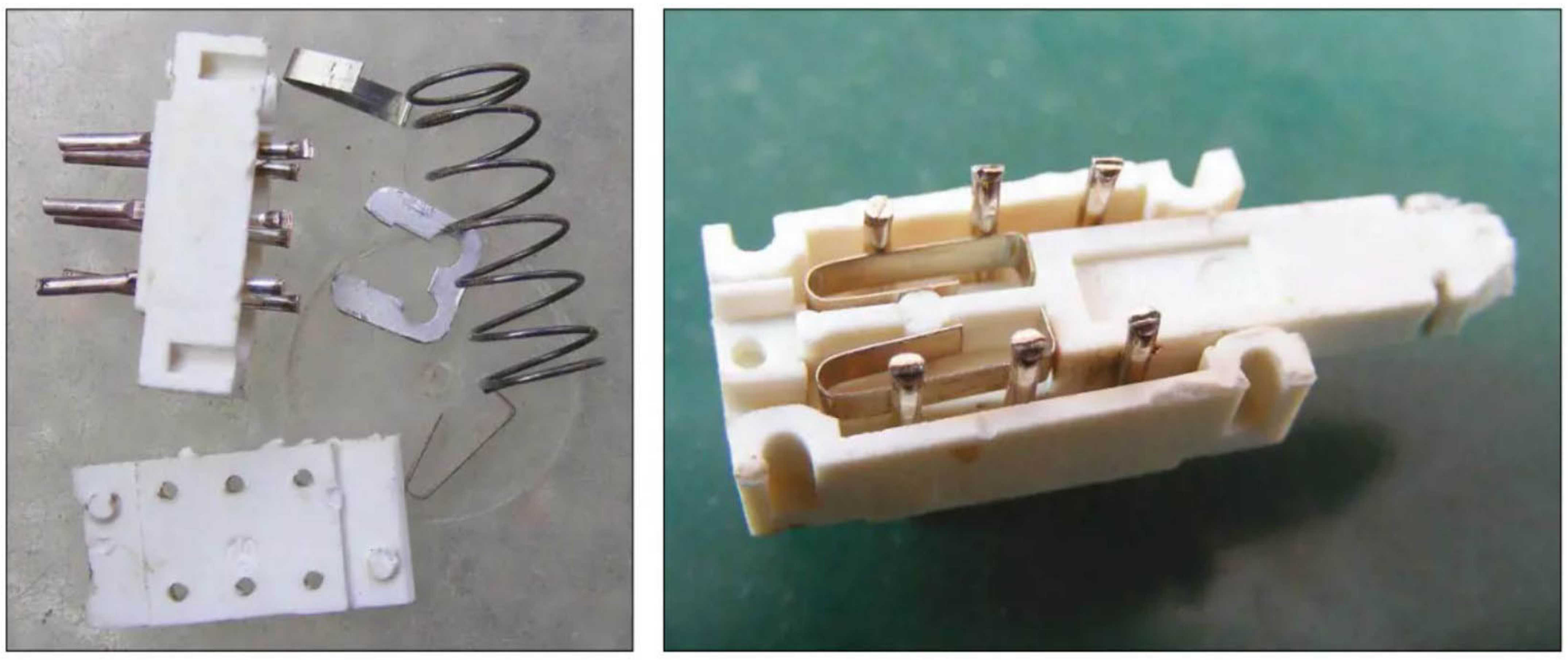

Fig.45 (left) The small parts of the AMS1 switch ejected. Note the spring and specially bent contact strips. The originals was never found. These are the internals of a replacement; (right) switch with the top prised off to show the sliding contacts of the DPDT switch. This is in the on (pushed in) position.

tab was (Fig.44). Even then I couldn't get the slider back in until I realised I had to raise the Vero pin for clearance. It then had to be pushed down when the slider was inserted with new springy contacts from a sacrificed switch (Fig.45) and precariously held in place. I had to drill a 1.2mm hole to do this (Fig.46). It was a real pain to troubleshoot and fix, but definitely better than desoldering the whole switch with the possibility of damaging the PCB, which really would have been difficult to fix.

Multi-function mayhem

Audio switches are often combined with potentiometers to give dual functions with one knob. Switching can be at either end of a pot's rotation – clockwise or anti-clockwise – or the shaft can be pulled/pushed to actuate the switch. Old audio gear often combined the mains power switch with the volume control: a classic case of design trumping function and a sure way to induce hum and bangs. It's fine for signal and control switching though, and adds to the designer's ergonomic arsenal. For example, the AMS1 is full of switched pots, as shown in Fig.47.

Allan Bradley series 70 ModPots were among the most popular types in good quality audio equipment, offering a lifetime of 100,000 cycles. However, they were very expensive.

Finally, it's possible to add a mains switch to a rotary switch – see Fig.48.

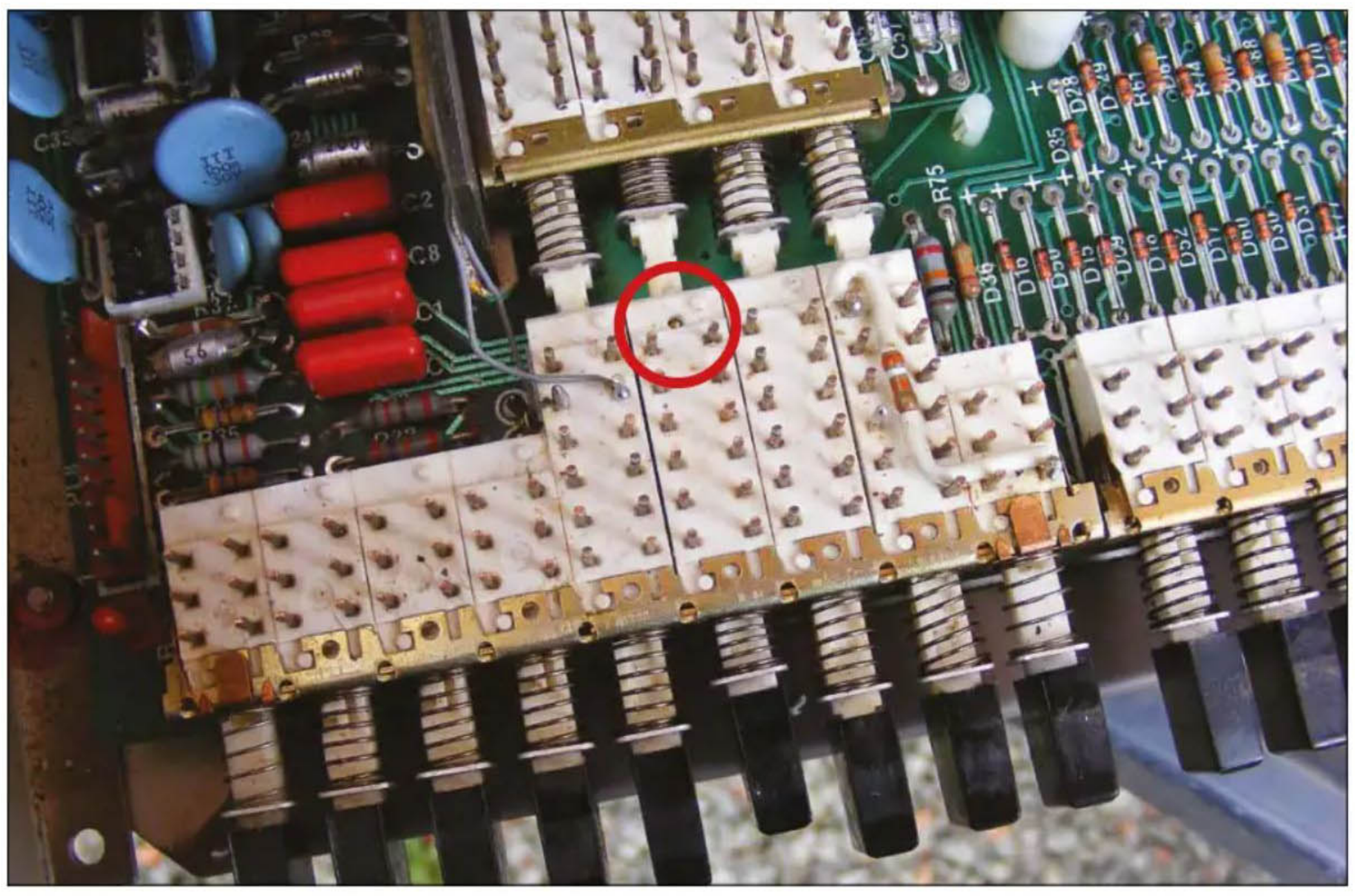

Fig.46. I had to drill another hole at the back (switch sixth from left) to access the Veropin to push it down after inserting the slider into the switch casing. No way was I going to unsolder 78 pins to get this switch assembly out.

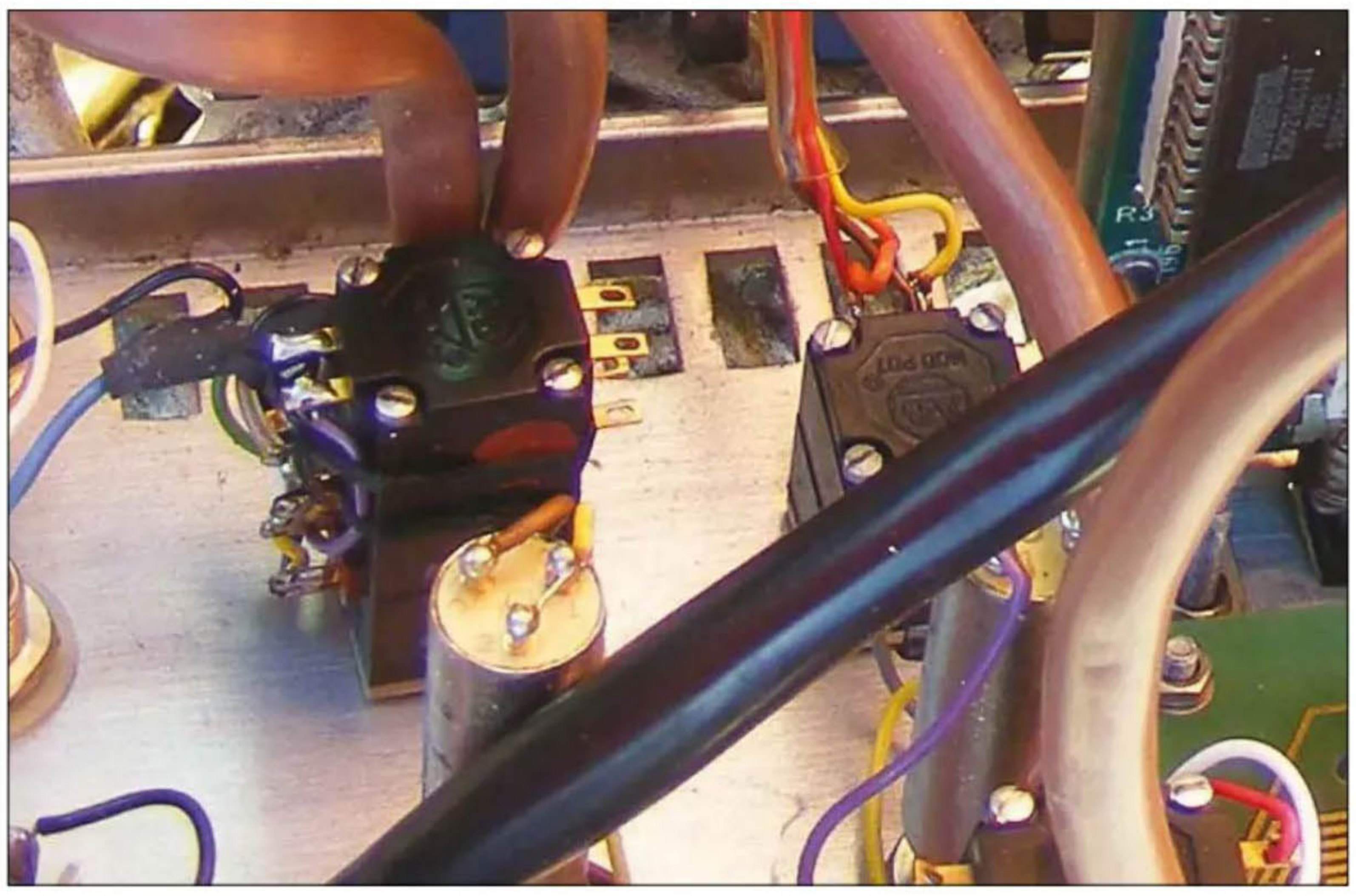

Fig.47. The Allan Bradley (now Clarostat/Honeywell) Mod Pot series enabled complex potentiometer and switch combinations to be made up for custom designs. (These are the black square devices).

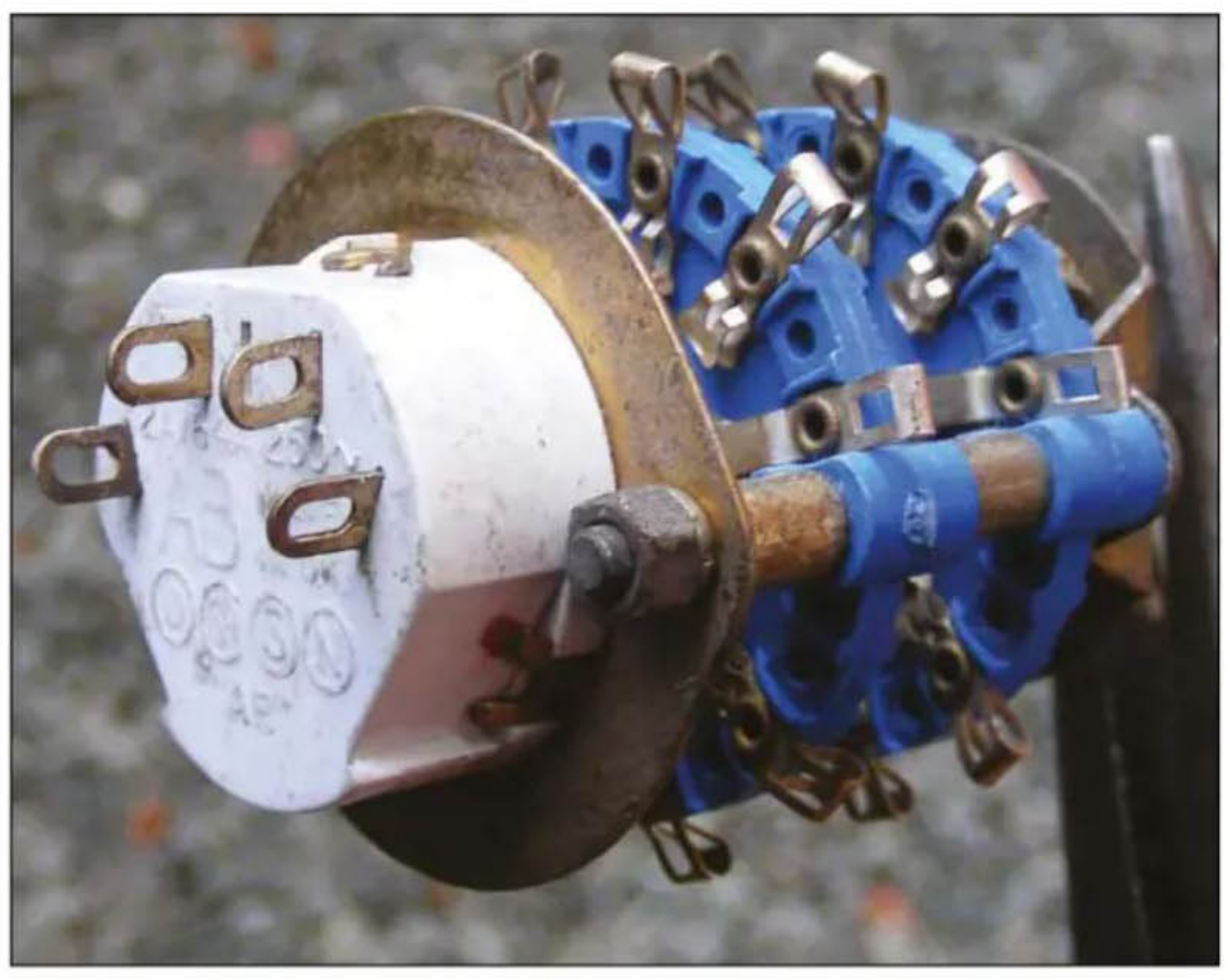

Fig.48. Here's a 5-way rotary switch with an integral mains switch on the first click. It's possible to get almost anything made up. This one was from Blore Edwards.

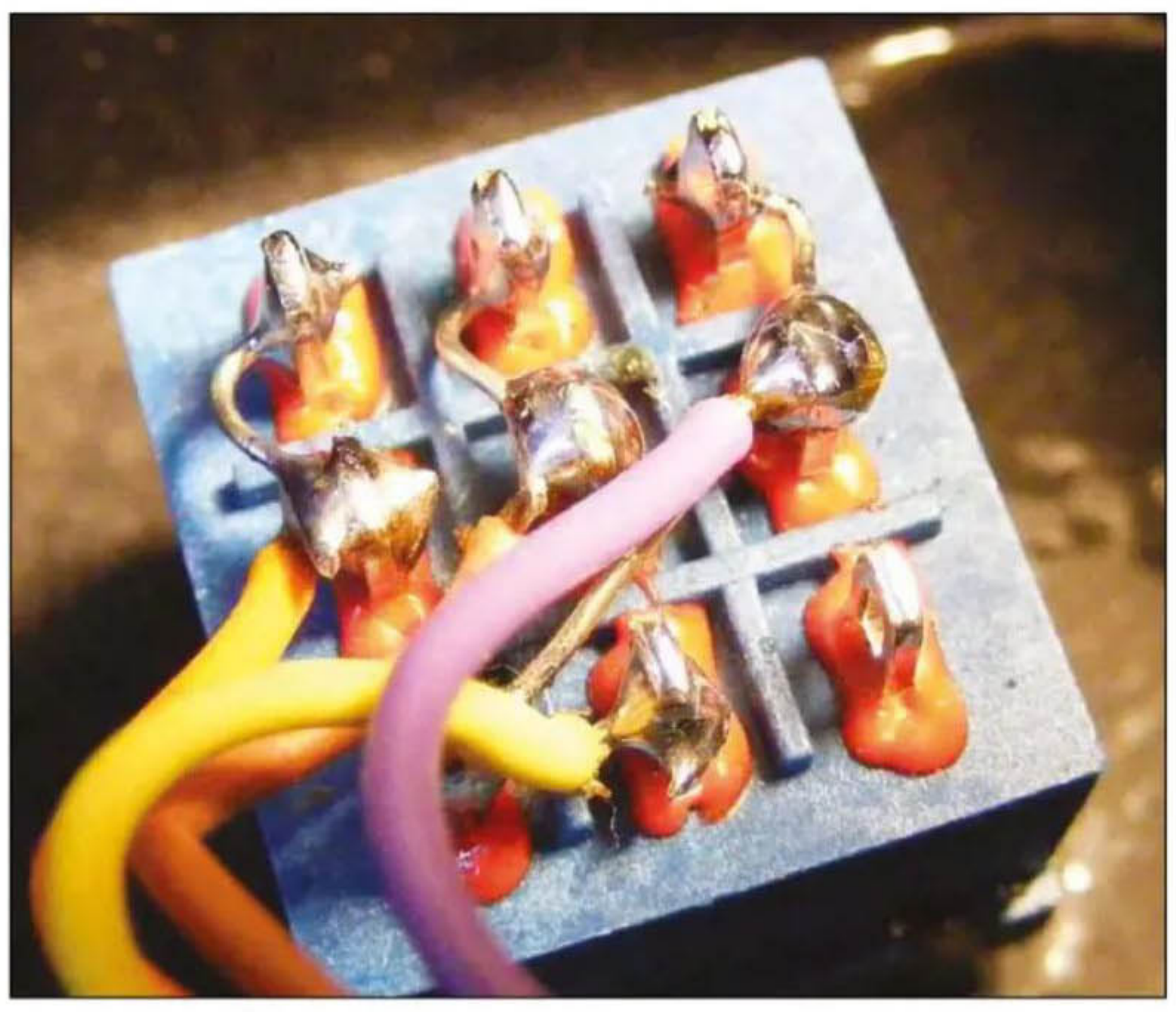

Fig.49. The spare section on this 3PDT hard bypass footswitch on this Macaris Colorsound wah-wah pedal is wired in parallel to improve reliability.

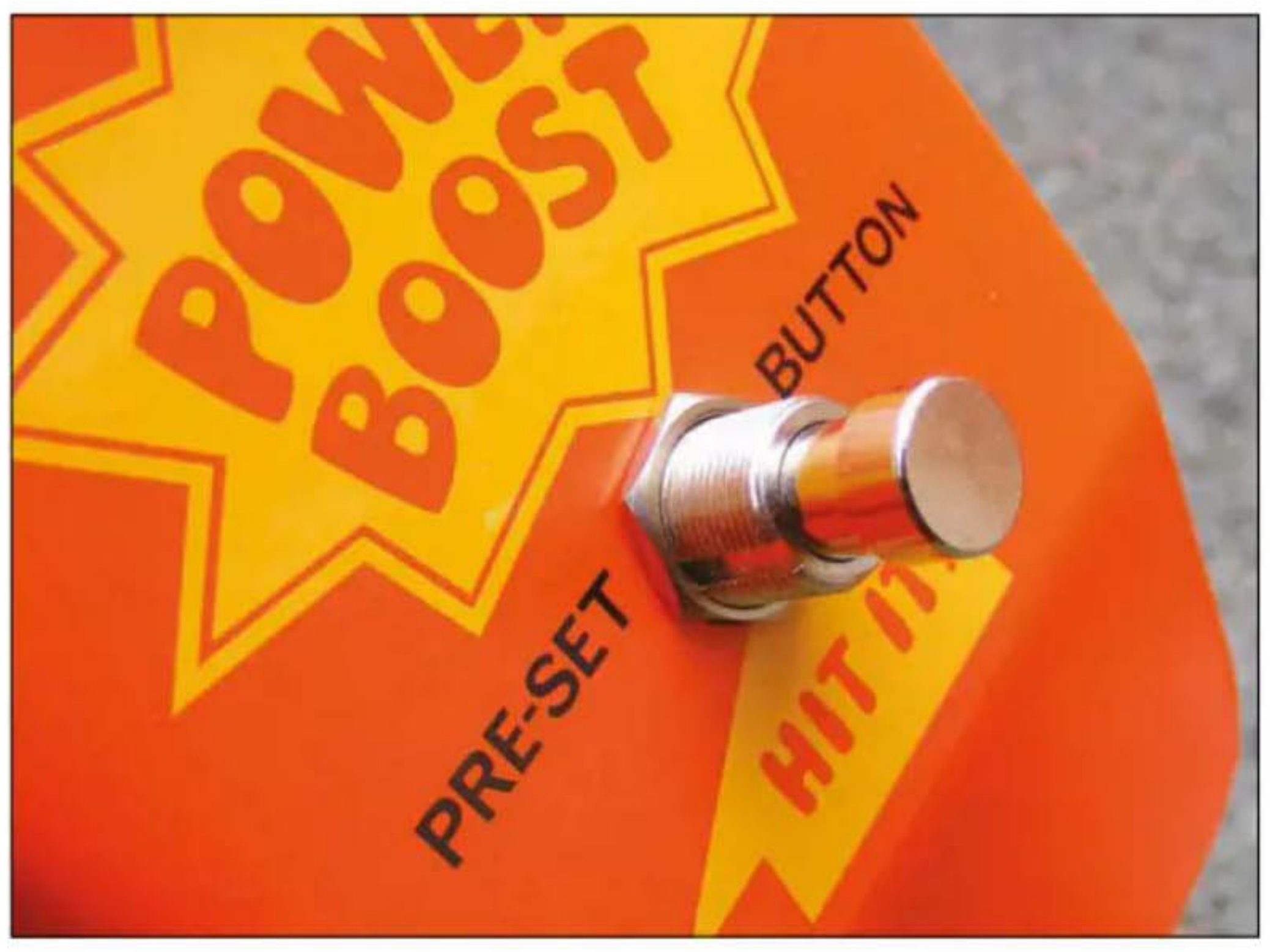

Fig.50. A Chinese Daier foot switch used on a Colorsound Powerboost preamplifier pedal. Guitar pedal builders call these 'stomp' switches. (Do not adjust your monitor, I've always built 1970s-style electronics in orange cases. Matt black is only for heatsinks).

Unused contacts

There are often spare sections on multi-pole switches. Don't waste them, wire them in parallel as shown in Fig.49 to improve reliability and reduce contact resistance. The switch here is a 3PDT guitar pedal bypass switch from Daier Electron in China – see Fig.50. This switch also has an improvement to the classic bypass circuit shown originally in Fig.9 last month. Here the input circuitry can be a single switch contact. If a changeover contact is used, the unused contact can be grounded to stop noise pick up that may result in a pop when the effect is engaged, as shown in Fig.51. I now use this method in all my Colorsound guitar effects pedals.

Next month

My overview of audio mechanical switches went on longer than expected, but next month we really will move on to the topic of audio electronic switching.

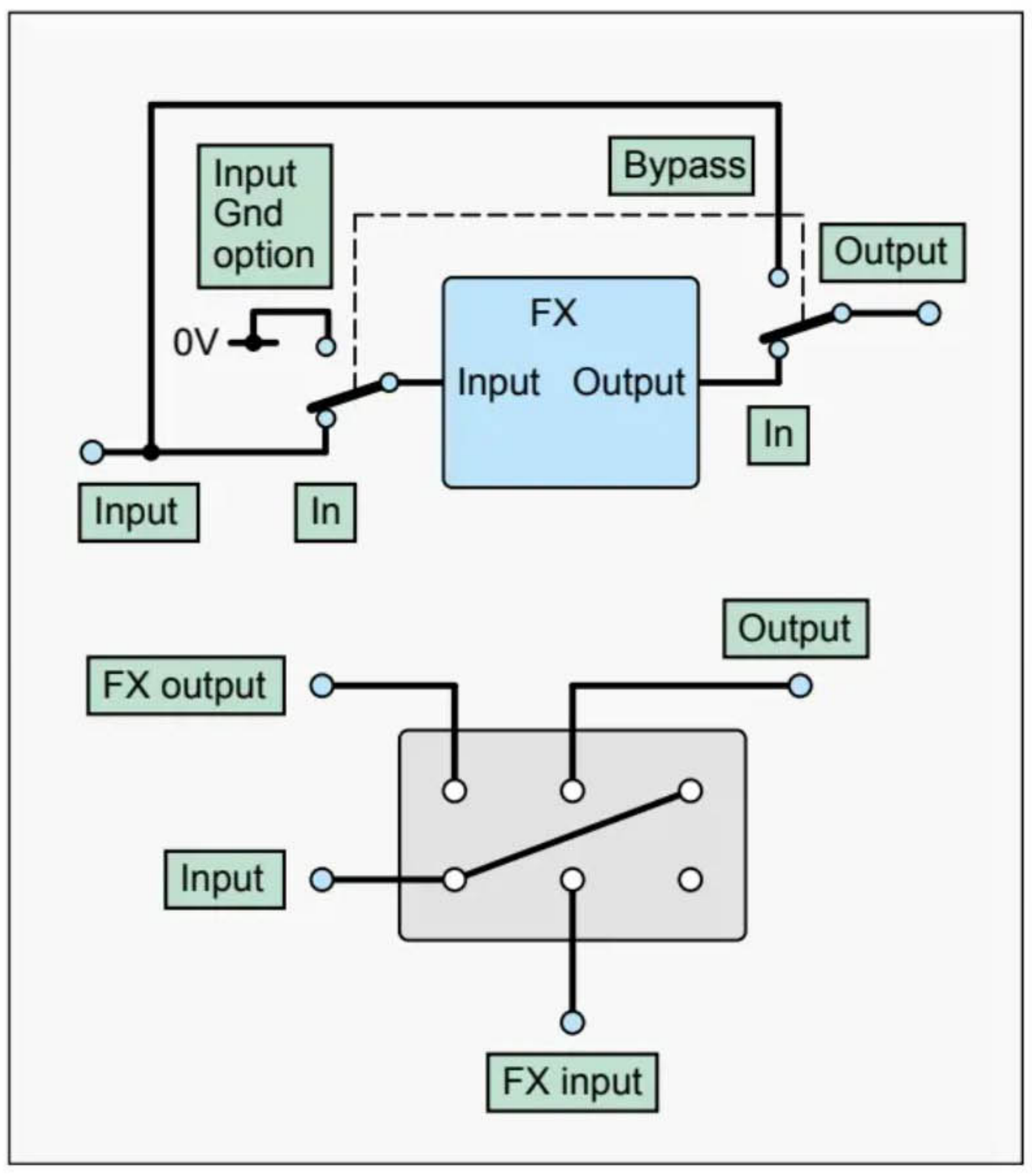

Fig.51. Superior hard bypass. Avoids one extra contact in bypass mode compared to a traditional circuit. If a DPDT switch is used, the unused contact can be used to earth the processors input.

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Max's Cool Beans

By Max the Magnificent

Arduino Bootcamp – Part 19

Do you know what you were doing at 5:16:20 pm on Saturday, 23 November 1963? I do. I was six years old, and I was standing bravely (cowering) behind the sofa with my teddy bear captivated by the sound of the electronic opening music accompanying the very first episode of the British science fiction television series, *Doctor Who.* I've been a devoted fan ever since. Why did this just pop into (what I laughingly refer to as) my mind? Well…

A gaggle of techno-geeks

There is no official collective noun for a group of engineers, but two terms I favour are 'a sprocket of engineers' and 'a rube of engineers,' where the latter derives from the American cartoonist, sculptor, author, engineer and inventor, Reuben Garrett Lucius Goldberg (a.k.a. Rube Goldberg). Rube is best known for his cartoon depictions of complicated gadgets performing simple tasks in indirect and convoluted ways.

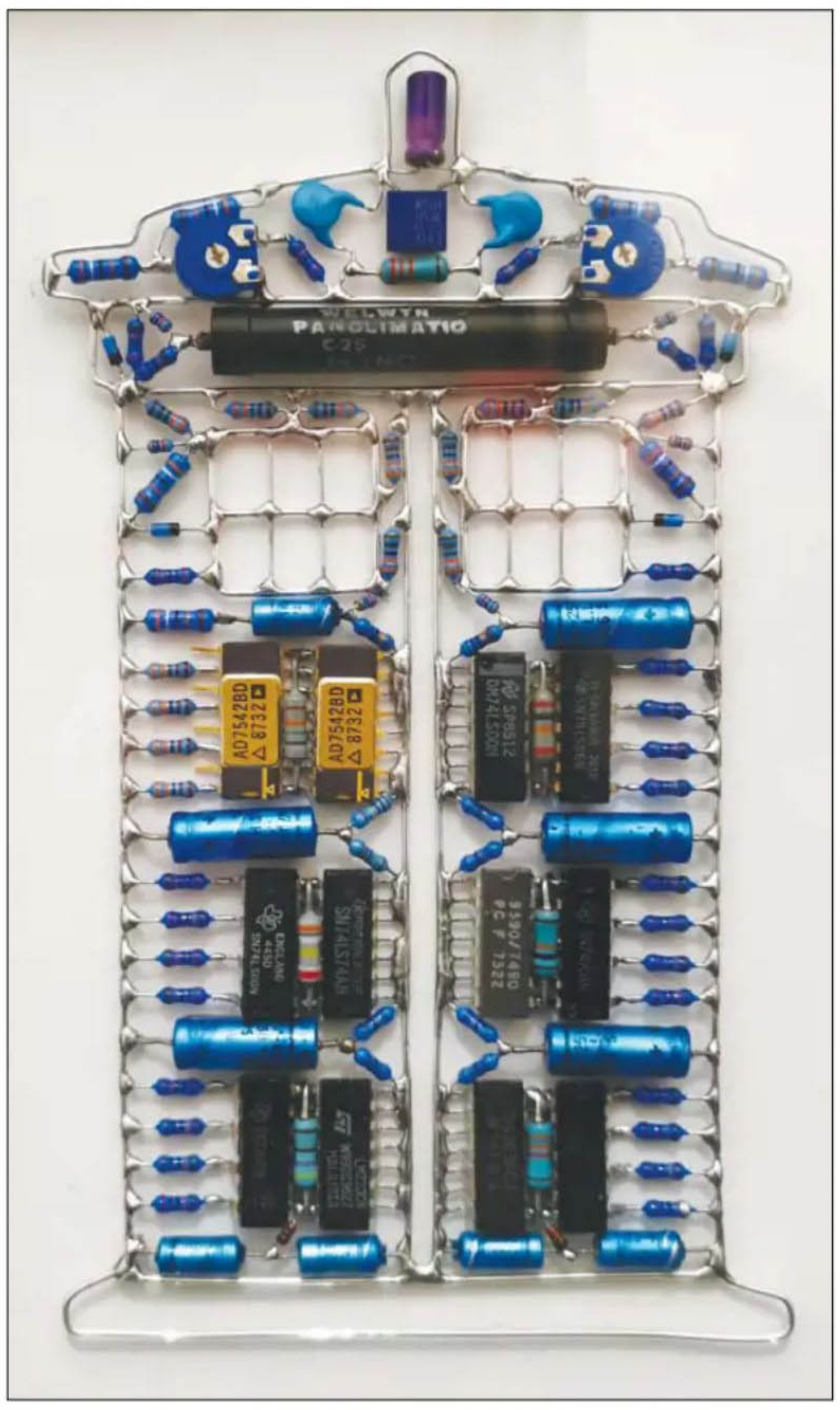


Fig.1. Electronic component artwork for the Doctor Who TARDIS (Source: Paul Parry).

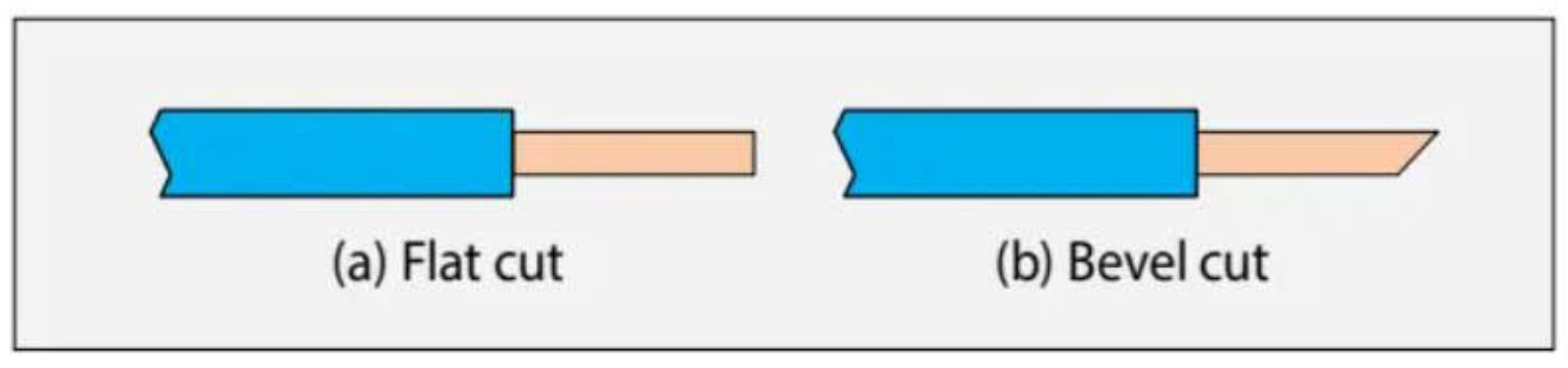


Fig.2. A cut above the rest.

As I've mentioned before, whenever I return to England to visit my dear old mom, on the Friday before I return to America, a gaggle of my techno-geek friends flock from across the country. We all meet at the house of my brother, Andrew, where we spend a happy day and evening showing off our latest and greatest creations and telling tall tales of derring-do. Why do I mention this here? Well…

Electronic component art

One of the guys who attends our geeky gatherings is Paul Parry, who is the founder and owner of Bad Dog Designs (**https://bit.ly/3QsB8kw**). Over the past decade, Paul has captivated and cultivated a worldwide following for his Nixie-tube-based timepieces.

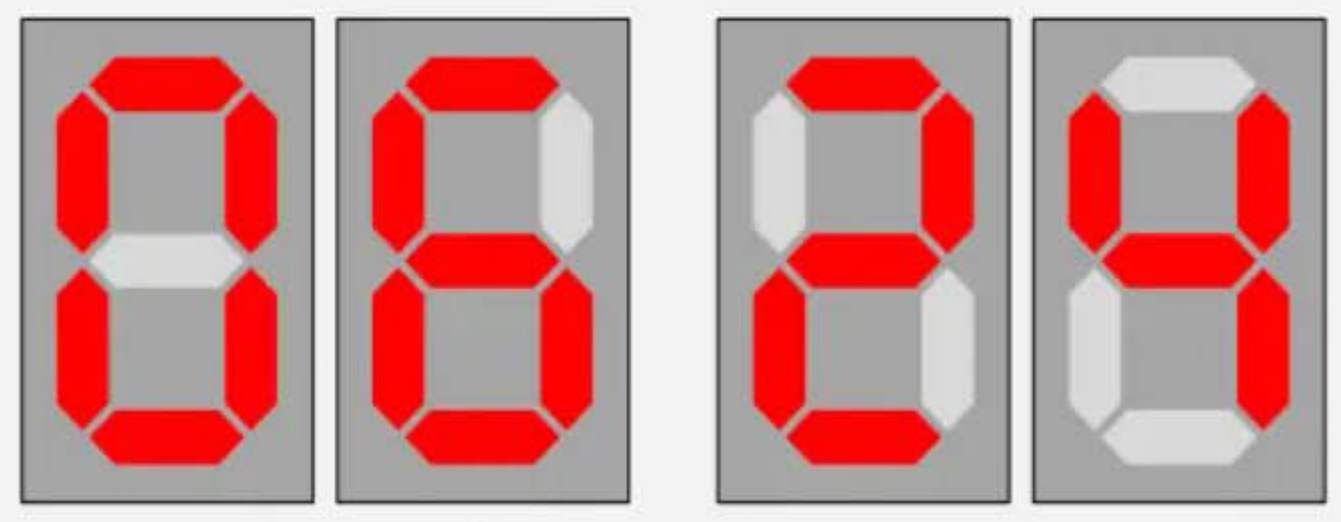
More recently, Paul has started a new line in electronic component-based artworks (**https://bit.ly/4dryK7t**). I love all these creations, but the one that really caught my eye was that of Doctor Who's TARDIS (Fig.1). I have one on order for when I visit the UK this summer.

Meanwhile, back in America, I meet up with a group of friends on Tuesday evenings. We have a light supper and then watch two episodes of Doctor Who (we started with the 2005 reboot starring Christopher Eccleston). These guys are going to be blown away when I flaunt my new acquisition.

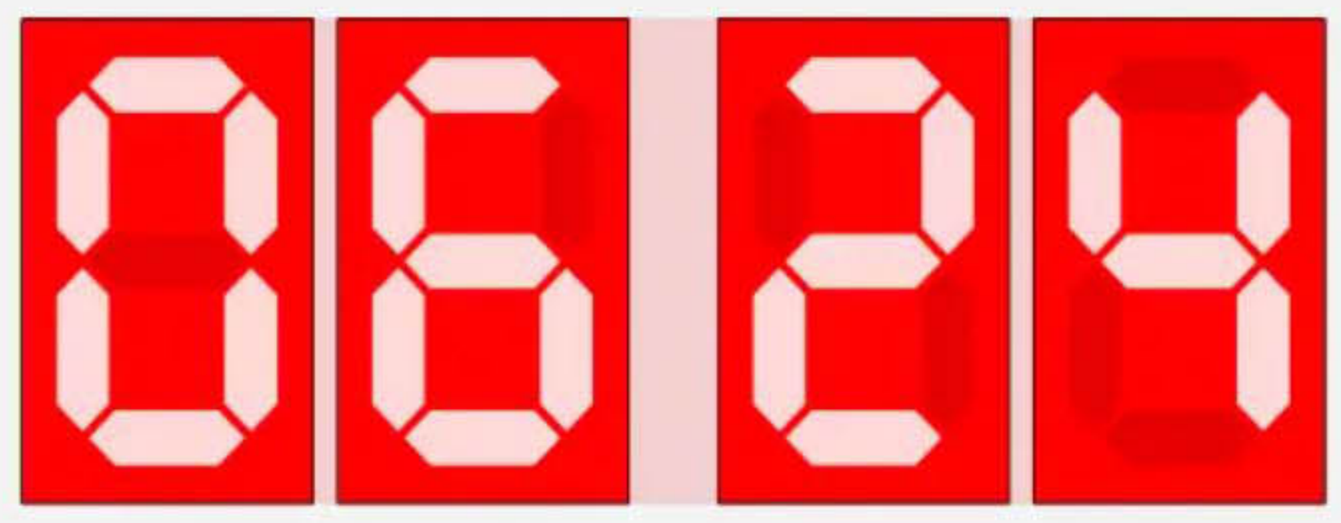
A handy-dandy tip

In my previous column (*PE*, June 2024), I remarked on how my friend Joe Farr has a vast amount of practical knowledge. I also commented on the kits of pre-stripped, pre-formed, solid core jumper wires you can find on Amazon (**https://bit.ly/3vDs2KK**).

While we were chatting about 'this and that,' Joe dropped a little nugget of knowledge into the conversation. He noted that he always cuts his solid core jumper wires at a 45° angle if he's using them with breadboards (Fig.2). This is because (a) they slide in more easily and (b) square ends have the potential to damage the breadboard's sockets. I tell you; I learn something new every day!



(a) Without insulating tape



(b) With insulating tape

Fig.3. The old insulating tape trick.

Seeing red

Joe also taught me another tidbit of trivia. He says he usually covers the front of his red light-emitting diode (LED) 7-segment displays with a piece of red insulating tape.

I must admit to being surprised. 'I'm surprised,' I said (so it must be true). I told Joe I'd assumed insulating tape was opaque. He replied that although the tape does dim the displays a little, it also makes the active segments 'pop.'

I just tried this myself and I see what Joe means. I've tried to replicate this effect in Fig.3 (only partially successfully, I fear). The situation without insulating tape is shown in Fig.3a. In this case, the active segments are a little brighter, but the inactive segments still manage to stand out. By comparison, when the insulating tape is applied as depicted in Fig.3b, even though the active segments are a tad dimmer, the inactive segments become almost invisible, thereby making their active counterparts more prominent. Once again, I learn something new every day!

Resistance is futile!

Toward the end of my previous column, I showed a picture of my own breadboard setup with four multiplexed 7-segment displays presenting the hours and minutes in HH:MM format. At that time, I directed your attention to a rinky-dinky

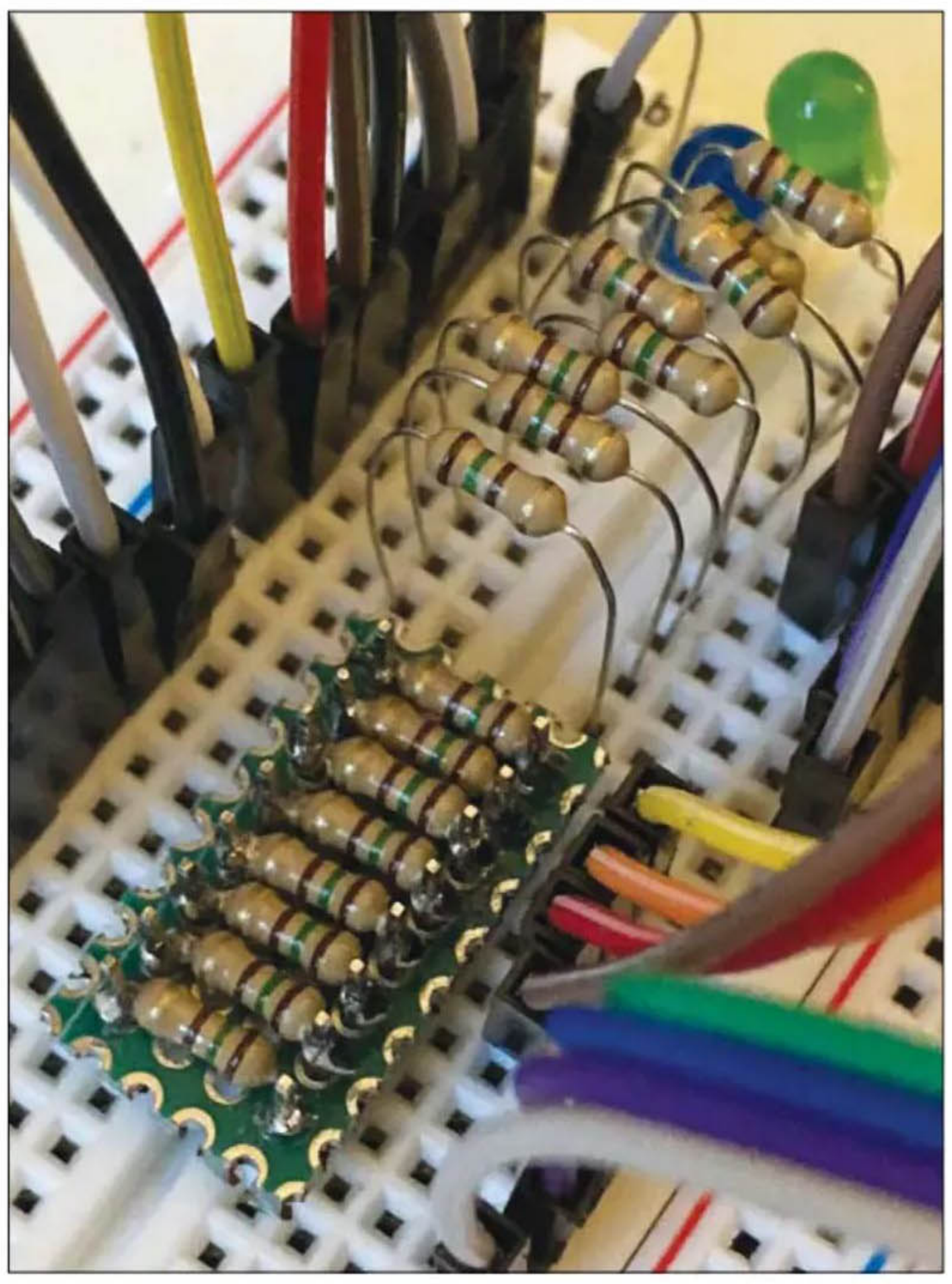


Fig.4. Replacing free-standing resistors with a BOB.

little board in the upper right-hand corner of my breadboards.

As you may recall, at one stage in our experiments we had two groups of eight 150Ω current-limiting resistors (this was before we realised that we needed only one such group). We started off using free-standing resistors, as shown in the upper portion of Fig.4.

In addition to looking untidy, one problem with having a bunch of resistors in proximity like this is that it's easy for the leads of adjacent resistors to make unwanted connections with each other. This can result in annoying issues, especially if the connections are intermittent.

One solution is to replace the free-standing resistors with dual in-line (DIL) resistor packages. An example is provided by the Bourns 4100R Series (**https://bit.ly/4biAmPH**). These are available in different-sized packages with different numbers and configurations of resistors. For our purposes here, we would like a 16-pin package containing eight isolated 150Ω resistors.

The main problem with this approach is that the range of resistance values supported by the Bourns 4100R Series (and similar offerings from other manufacturers) is limited.

A cheap-and-cheerful alternative is to build our own breakout board (BOB) carrying eight discrete 150Ω resistors, as shown in the middle of Fig.4. In addition to preventing any leads shorting, using BOBs like this makes it easy to replace one group of resistors with another, which is something we may well be doing a lot of in the not-so-distant future (I feel like an oracle… but where are we going to find one at this time of the day?).

Building a BOB

As an aside, I have more than my fair share of friends called Bob. When I'm talking to my wife (Gina the Gorgeous), I need to qualify which Bob is the topic of discussion, so I call them Bible Bob, Carpenter Bob, Sparkly Bob… I recently ran across a science fiction book called *We Are Legion (We Are Bob)*. I had to buy this book just for the title. It was only after it had arrived that I discovered it's an awesome story. And I'm not the only one who thinks so because this tome has 4.5 stars with 24,000+ ratings on Amazon (**https://bit.ly/3wsnoiQ**).

But we digress. To build our BOB, we will need to start with a piece of board. One contender is stripboard (**https://bit.ly/3JLtbTJ**), but this would require us to cut tracks using a knife or a special stripboard track cutting tool (**https://bit.ly/3UprIYh**). In this case, however, I opted for a piece of prototyping board (**https://bit.ly/3UMkcZ1**).

Now we have another choice. We can either use a fine-toothed hacksaw to cut our board between the holes (Fig.5a), or we can use a utility knife to score lines through the holes and then snap the board along these lines (Fig.5b). In my case, I opted for the latter solution because I happened to have a utility knife in my pocket whilst my hacksaw was hiding in the tool chest in the garage (thus are our decisions made).

We're also going to need cut two 8-pin pieces of the same long-tailed (0.1-inch pitch) header pins we used to create the breadboard power LED assemblies in our previous column (**https://bit.ly/3U1Vp2z**). Stick these 8-pin header pin strips into an old breadboard mounted four holes apart. The reason for using an old breadboard is that we are about to do some soldering. Bits of solder and fragments of wire can fall into the breadboard's holes, so we will want to reserve this board for soldering and similar non-active activities in the future. This means it would be a good idea to mark 'Do Not Use' on this board for future reference.

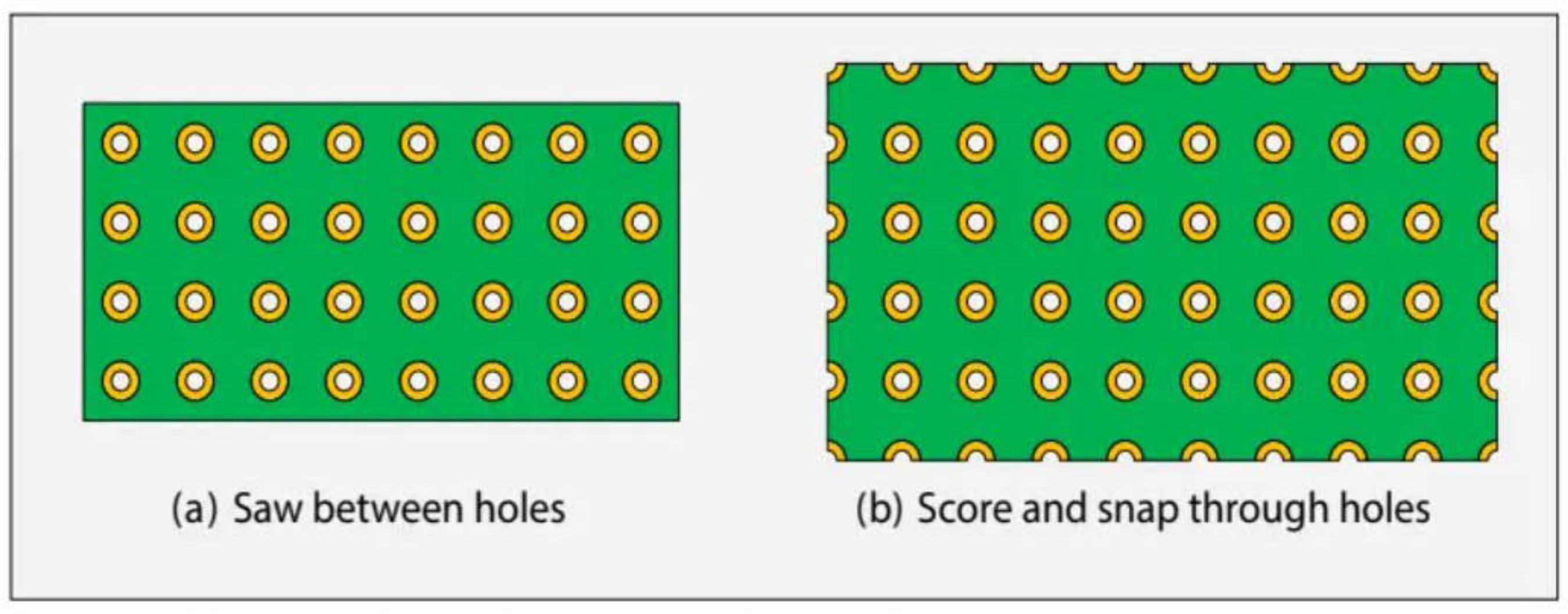


Fig.5. Preparing the BOB board.

Now, this next part is important, so sit up and pay attention. You may be tempted to solder the resistors and the board to the header pins at the same time. Fight this temptation with all your might. If you do solder them simultaneously, there's more than a batting chance the solder won't wick (get sucked through) the via all the way to the other side. In turn, when you eventually plug your BOB into your project's breadboard, the header pins may separate from the BOB (sad face).

Thus, our first task is to solder the board to the header pins (Fig.6a). Use a hot soldering iron and hold it on each joint long enough for the solder to wick all the way through the via (remember we talked about soldering, along with Alan Winstanley's handy-dandy *Basic Soldering Handbook*, in *PE*, March 2024).

When it comes to attaching the resistors, you have another decision to make because there are various ways to do this. Joe comes from a prototyping background where things often need to be reworked. Based on this, he favours simply bending the resistor leads at 45° angles, soldering them to the pins, and cutting off any excess lead (Fig.6b). The advantage of this approach is that it's easy to desolder things if required later.

By comparison, I tend to come from a more mission-critical and safety-critical background where 'Failure is not an option.' Based on this, I tend to overengineer things, such as twisting the leads through a full 360° circle (Fig.6c). The downsides to this approach are that it's easier to create solder bridges between adjacent pins (because the joints are bigger) and it's harder to rework the BOB later. The upside is that these solder joints are not going to fail anytime soon.

Just to make sure we're all up to date, I've added this BOB to the drawing of the latest and greatest incarnation of our prototyping platform (file **CB-Jul24-01.pdf**). As usual, all the files

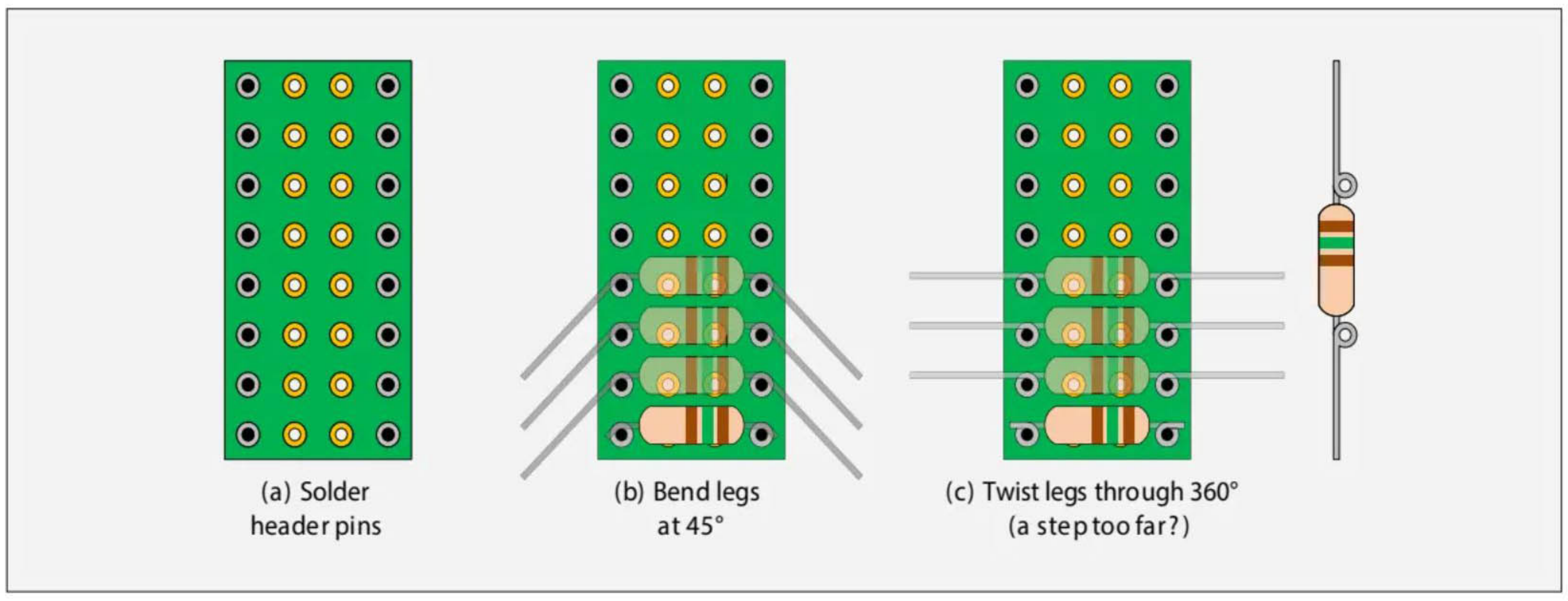


Fig.6. Adding the resistors to the BOB board..

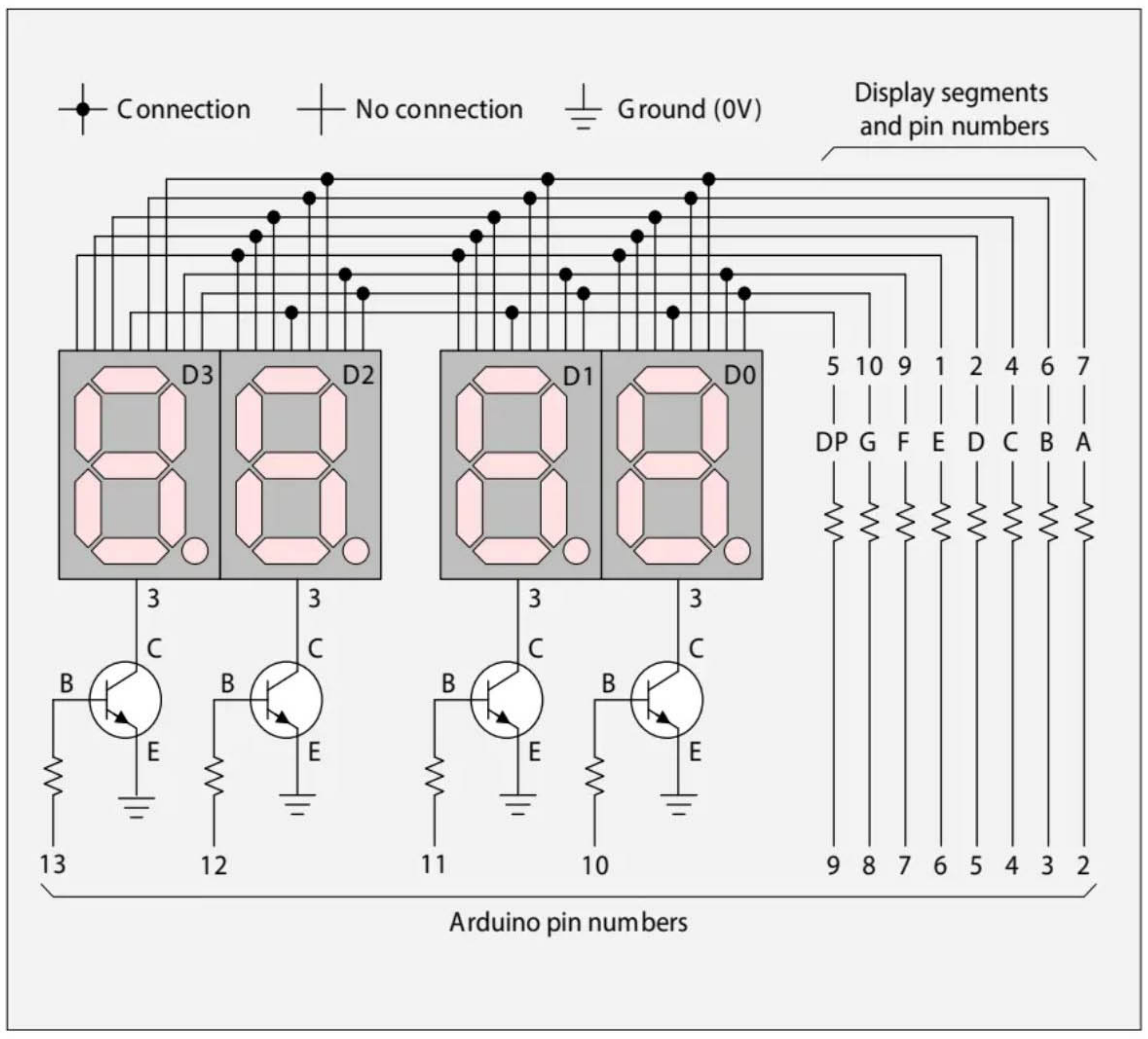
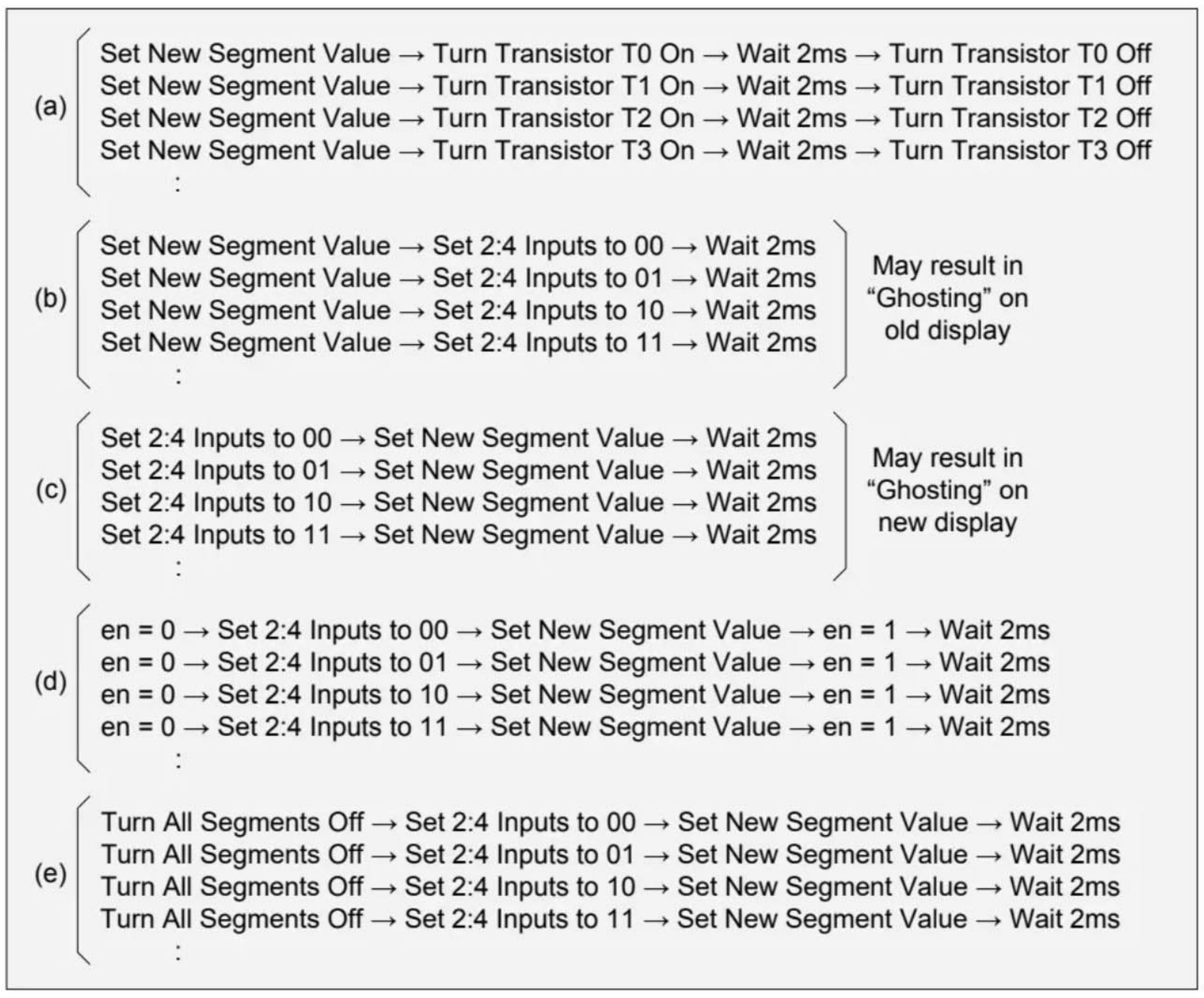


Fig.7. Current circuit with four 7-segment displays.


(a)
Set New Segment Value → Turn Transistor T0 On → Wait 2ms → Turn Transistor T0 Off
Set New Segment Value → Turn Transistor T1 On → Wait 2ms → Turn Transistor T1 Off
Set New Segment Value → Turn Transistor T2 On → Wait 2ms → Turn Transistor T2 Off
Set New Segment Value → Turn Transistor T3 On → Wait 2ms → Turn Transistor T3 Off
:

(b)
Set New Segment Value → Set 2:4 Inputs to 00 → Wait 2ms
Set New Segment Value → Set 2:4 Inputs to 01 → Wait 2ms
Set New Segment Value → Set 2:4 Inputs to 10 → Wait 2ms
Set New Segment Value → Set 2:4 Inputs to 11 → Wait 2ms
:
May result in "Ghosting" on old display

(c)
Set 2:4 Inputs to 00 → Set New Segment Value → Wait 2ms
Set 2:4 Inputs to 01 → Set New Segment Value → Wait 2ms
Set 2:4 Inputs to 10 → Set New Segment Value → Wait 2ms
Set 2:4 Inputs to 11 → Set New Segment Value → Wait 2ms
:
May result in "Ghosting" on new display

(d)
en = 0 → Set 2:4 Inputs to 00 → Set New Segment Value → en = 1 → Wait 2ms
en = 0 → Set 2:4 Inputs to 01 → Set New Segment Value → en = 1 → Wait 2ms
en = 0 → Set 2:4 Inputs to 10 → Set New Segment Value → en = 1 → Wait 2ms
en = 0 → Set 2:4 Inputs to 11 → Set New Segment Value → en = 1 → Wait 2ms
:

(e)
Turn All Segments Off → Set 2:4 Inputs to 00 → Set New Segment Value → Wait 2ms
Turn All Segments Off → Set 2:4 Inputs to 01 → Set New Segment Value → Wait 2ms
Turn All Segments Off → Set 2:4 Inputs to 10 → Set New Segment Value → Wait 2ms
Turn All Segments Off → Set 2:4 Inputs to 11 → Set New Segment Value → Wait 2ms
:

Fig.9. Alternative control scenarios.

mentioned in this column are available from the July 2024 page of the *PE* website: **https://bit.ly/pe-downloads**

Why don't we…

I received an interesting email from a reader we will call James (because that's his name). James had a question regarding our current circuit (Fig.7). As you will recall, in the present incarnation of our clock, we are using eight of our Arduino's digital input/output (I/O) pins to drive the display segments, with all four displays connected in parallel (side-by-side). Also, we are using four digital I/O pins to control the transistors we use to activate the displays. This means we are using 12 digital I/Os in all.

As we've previously noted, the Arduino Uno has only 14 digital I/O pins (remember that we aren't considering the 6 analogue pins, which can also be used as digital I/Os, because we are holding them in reserve for a later date). Also, we aren't using digital I/Os 0 and 1 because these are reserved for communications between the Arduino and the host computer.

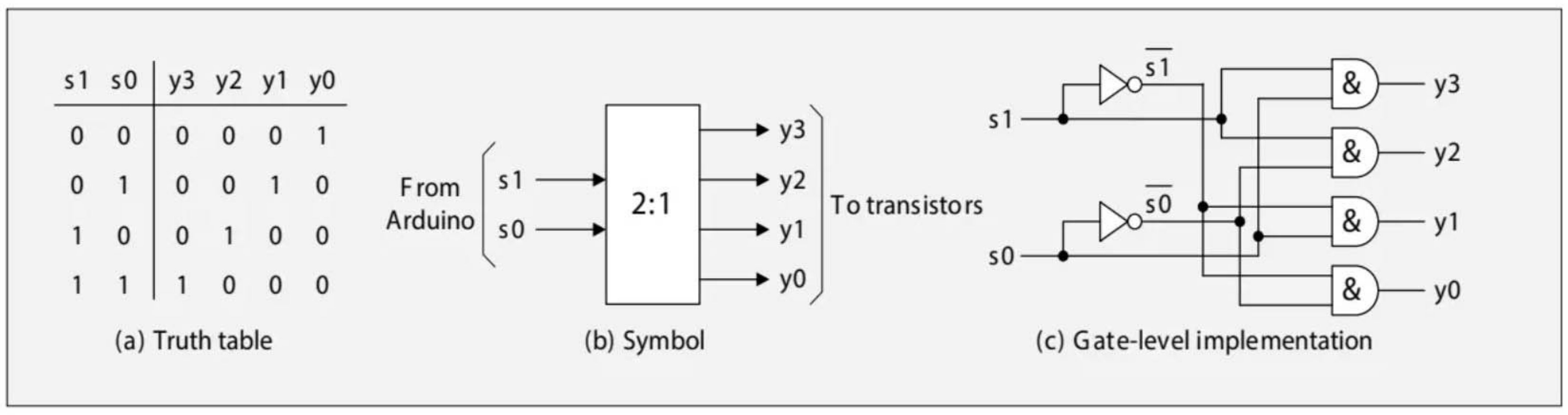
So, the situation we find ourselves in is (a) the Arduino Uno has 12 digital I/Os available to us and (b) we are using all of them to drive our four displays. This means we don't have any digital I/Os free to implement other functions, like driving our piezoelectric buzzer, for example (we introduced this component in *PE*, December 2023).

In a crunchy nutshell, the question posed by James the inquisitor can be summarised as follows: 'Why don't we use a 2:4 decoder to drive the transistors, thereby freeing up two of the Arduino's digital I/Os?'

That's a good question. Remembering that I'm only ever an email away, I'm surprised you haven't presented this poser yourself. Using a 2:4 decoder (we read this as 'two-to-four decoder') is certainly a possibility, although there are some considerations to… well, consider. On the off chance this function is new to you, let's start by considering what we mean by a 2:4 decoder in the first place.

The idea is to create a logic function that has two inputs and four outputs. The inputs, which we will drive using our Arduino, have $2^2 = 4$ possible combinations: 00, 01, 10, and 11. We want to use each of these input combinations to select one of our four possible outputs, which we will use to control the transistors that control our displays. Furthermore, in the case of our current circuit, we require 'active high' outputs, which means their active state is 1 and their inactive state is 0. This is due to the way we have things wired, whereby a 1 will turn the corresponding transistor on. Remember, we want only one transistor (and thus one display) to be active at a time.

It may (or may not) be worth noting that our hypothetical 2:4 decoder can be thought of as implementing a 'one hot' code in that only one of the four outputs is 'hot' (active) at any time.



s1	s0	y3	y2	y1	y0
0	0	0	0	0	1
0	1	0	0	1	0
1	0	0	1	0	0
1	1	1	0	0	0

(a) Truth table

(b) Symbol

(c) Gate-level implementation

Fig.8. 2:4 decoder with active-high outputs (driving 4 displays).

Based on the functional specification we just established for our 2:4 decoder, we can create a truth table (Fig.8a), a symbol (Fig.8b), and a gate-level implementation (Fig.8c), where s stands for 'select' and y stands for 'output.' In this case, we are using two NOT (inverter) gates and four 2-input AND gates. You can find a quick refresher on the truth tables and functioning of NOT, AND, NAND and XOR gates in my *Cool Beans Blog* on the C/C++ bitwise operators (**https://bit.ly/3UqT9B6**). A more in-depth discussion is provided in my book *Bebop to the Boolean Boogie* (**https://bit.ly/4a6wDDm**).

So, in the case of our current four-display clock, we now have a choice between *not using* a 2:4 decoder and having *no* free digital I/Os or *using* a 2:4 decoder and having *two* free digital I/Os.

As a slight aside, if we ever decide we want to drive anywhere from five to eight displays, the way we are currently implementing things would leave us with no choice but to use a 3:8 decoder (three inputs and eight outputs), which would still leave us with one free digital I/O.

Seeing ghosts

Remember that we are just spitballing ideas here. We aren't really going to deploy a 2:4 decoder, but it's well worth taking the time to cogitate and ruminate over the implications if we were to do so.

Your knee-jerk reaction might be that using a 2:4 decoder as discussed above would be easy peasy lemon squeezy. Hold hard! Not so fast! Remember that I said there were considerations to consider. Take a moment to think about (a) our gate-level implementation and (b) how we might use the Arduino to drive the inputs to the decoder. Can you envisage any potential problems?

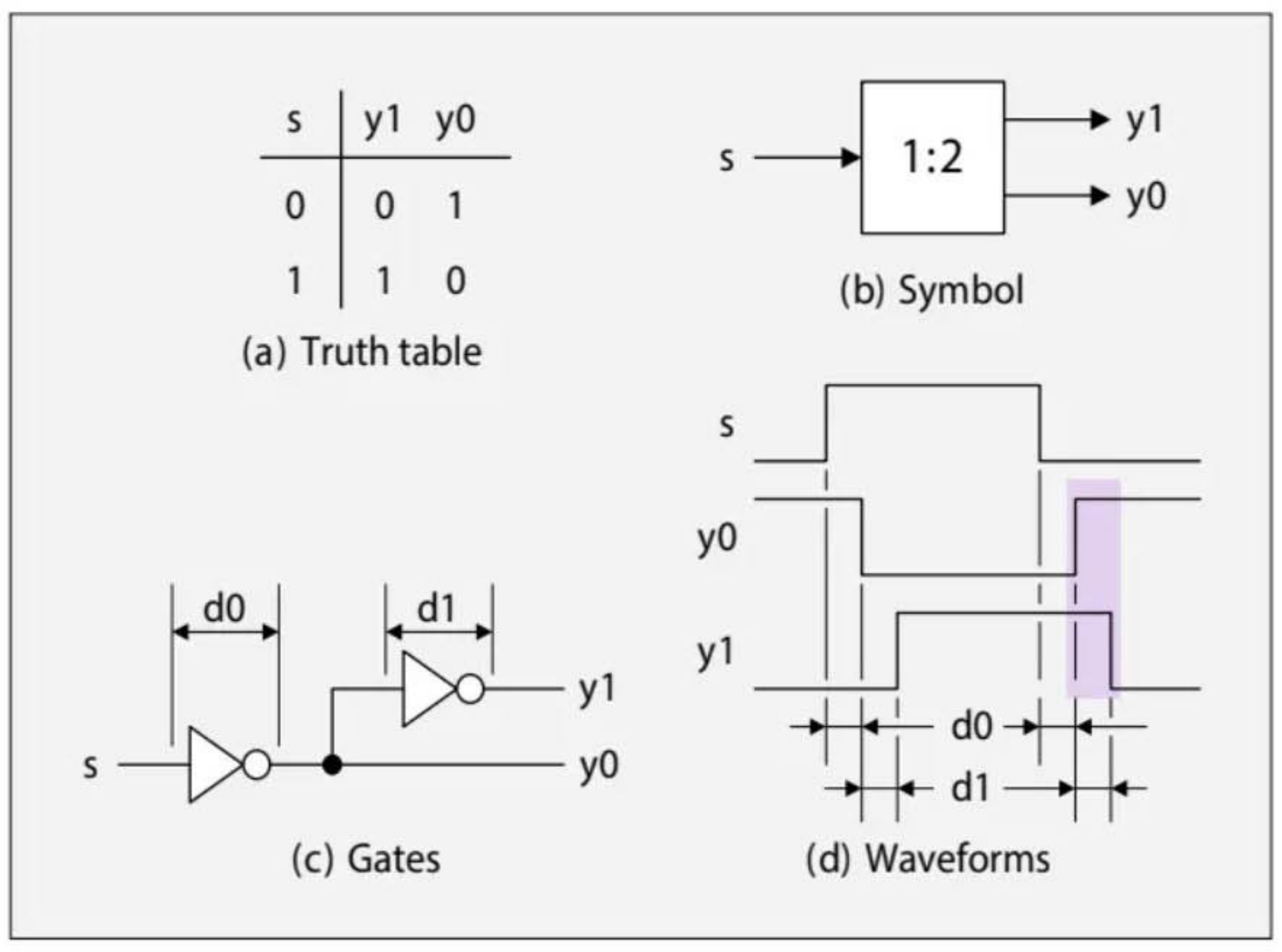


Fig.10. 1:2 decoder with active-high outputs (driving 2 displays).

Hold onto your hat because I'm about to make your head spin and your brain wobble on its gimbals. Let's start by reminding ourselves that the way our program is driving our existing circuit can be summarised as shown in Fig.9a (observe we are using the two-millisecond (2ms) on/active time for our displays that we settled on in our previous column).

The key point with respect to our existing implementation is that it's possible for us to turn all the transistors off at the same time. Now consider our 2:4 decoder-based solution. In this case, there will always be one of our displays that's active.

In the context of this column, the term 'ghosting' refers to our trying to display two values too closely together on the same display, one for a longer time (the desired value) and one for shorter duration (the fainter, 'ghost' value).

For the moment, let's assume that we are always driving our segments with on/off values associated with one of the digits 0 through 9. In this case, we have two options. We could set the segments to their new values and then set the 2:4 decoder's inputs to *their* new values (Fig.9b), but this may result in ghosting on the old display. Alternatively, we could set the 2:4 decoder's inputs to their new values *before* setting the segments to their new values (Fig.9c), but this may result in ghosting on the new display.

Could things get worse? You betcha!

One at a time

The way we've been thinking about things based on the truth table in Fig.8a and the sequences discussed in Fig.9b and Fig.9c is that the inputs to our 2:4 decoder will transition as follows: 00, 01, 10, 11, 00… In turn, this means we are activating our displays in the order D0, D1, D2, D3, D0…

Unfortunately, this leads us to fall into the trap of thinking that both inputs to our 2:4 decoder will change simultaneously. Thus far, however, we've learned how to change only one of our Arduino's digital outputs at a time.

What are the implications of this? Well, suppose that `s1` = 0 and `s0` = 1, which means display D1 is active. Now suppose we wish to deactivate display D1 and activate display D2. This means we want `s1` = 1 and `s0` = 0. To put this another way, we want the `s1-s0` inputs to our 2:4 decoder to transition from 01 to 10. One way to achieve this would be to use the following statements:

```
digitalWrite(S0, 0);
digitalWrite(S1, 1);
```

Unfortunately, this means the inputs to our 2:4 decoder would now follow the sequence 01, 00, 10, which means we would be driving our displays in the order D1, D0, D2.

Alternatively, we could swap the order of our statements to read as follows:

```
digitalWrite(S1, 1);
digitalWrite(S0, 0);
```

In this case, the inputs to our 2:4 decoder would follow the sequence 01, 11, 10, which means we would be driving our displays in the order D1, D3, D2.

Either way, we may now experience ghosting on two displays (let's call this 'double ghosting') rather than one (our original 'single ghosting' scenario), which means things are going from bad to worse.

Happily, there are two ways around this problem that immediately spring to mind. The first relies on the fact that it doesn't really matter in which order we activate our displays, just so long as we follow the same sequence repeatedly. So, rather than feeding the inputs of our 2:1 decoder with the binary sequence 00, 01, 10, 11, 00… (D0, D1, D2, D3, D0…), in which multiple bits change on the 01 to 10 and 11 to 00 transitions, we could instead use a Gray code sequence (named after Frank Gray), such as 00, 01, 11, 10, 00… (D0, D1, D3, D2, D0…), in which *only one* bit changes at a time.

An alternative solution relies on the fact that there is a way by which we can change multiple Arduino outputs simultaneously (although we don't want to get into that here). However, we would still have our original 'single ghosting' problem, and neither of these techniques would protect us from another potential 'gotcha' resulting from gate-level delays.

Don't delay

We often fall into another trap – that of thinking our primitive logic gates switch instantaneously. In the real world, however, there's always some element of delay. Just to make things a little simpler, let's perform a thought experiment. Let's imagine we have only two displays and consider the signals associated with a 1:2 decoder implemented using two NOT gates (Fig.10).

As we see, due to the delays associated with the NOT gates, there's a period when both the output signals are 1, which means both the displays will be activated at the same time. The same thing will apply to our 2:4 decoder (and a 3:8 decoder if we decided to use one); that is, there will be short periods where multiple displays are active simultaneously.

With respect to our earlier ghosting examples (both 'single ghosting' and 'double ghosting'), only one display was active at any time. In this case, however, we really do have multiple displays active simultaneously. This means that, in addition to a new form of ghosting, our Arduino's pins will have to drive twice the expected current.

Since we are talking about multiple outputs being simultaneously active for a duration of only a few nanoseconds due to this gate delay scenario, would either of the associated ghosting and current issues really be a problem? Probably not. On the other hand, I think it behooves us to engineer things in such a way that such a situation never occurs in the first place.

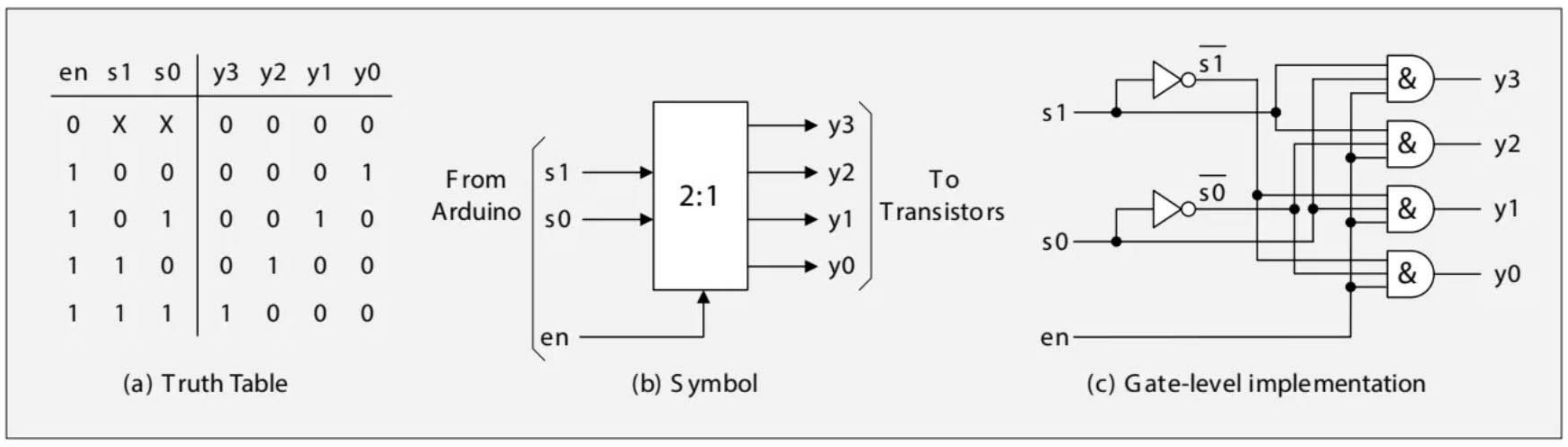
Adding an enable

There are two relatively simple solutions that will address both our sequencing and our gate-delay-induced problems. First, we could add an `en` ('enable') input to our 2:4 decoder. This signal would be controlled by our Arduino. In this case, let's say that if `en` is 0, all our outputs will be forced to their 0 (inactive) states. It's only when `en` is 1 that the selected output will be 1. The truth table, symbol, and gate-level implementation of this new incarnation of our 2:4 decoder function are shown in Fig.11.

In the case of the truth table (Fig.11a), `X` represents a 'Don't Care' state. Thus, we read the first row of this table as: 'When `en` = 0, we don't care what values are presented to `s1` and `s0` because we are going to force all the outputs to 0.' We read the remaining rows as: 'It's only when `en` = 1 that we use the values on `s1` and `s0` to activate one of our outputs.'

Having this enable signal allows us to use the control sequence presented in Fig.9d. This solution addresses all the ghosting and over-current issues we introduced earlier. However, there's a fly in the soup and an elephant in the room (I never metaphor I didn't like).

Remember that we started off using 4 of the Arduino's pins to directly drive our transistors. Then we moved to using only 2 of the Arduino's pins to drive our 2:4 decoder, which freed up 2 pins, but caused us to run into ghosting and other issues. By adding the enable to



en	s1	s0	y3	y2	y1	y0
0	X	X	0	0	0	0
1	0	0	0	0	0	1
1	0	1	0	0	1	0
1	1	0	0	1	0	0
1	1	1	1	0	0	0

Fig.11. 2:4 decoder with active-high enable and active-high outputs.

the 2:4 decoder, we are now using 3 of the Arduino's pins, leaving only 1 pin free, which prompts us to ask, 'Is all this worth the effort?'

The answer to this question is, 'It all depends.' If having a free pin is mission-critical and this is the only way to get it, then the answer would be 'Yes.' Otherwise, we might have to think about living without the decoder.

Drawing a blank

Are you drawing a blank with respect to the second solution that will address both our sequencing *and* our gate-delay-induced problems? If so, that would be ironic, because 'drawing a blank' is the solution.

Let us now return to our current implementation, but we'll assume it's been augmented with a simple 2:4 decoder (without an enable) as illustrated in Fig.12 (observe that we now enjoy two free pins).

Do you remember earlier when we said: 'For the moment, let's assume that we are always driving the segments associated with one of the digits 0 through 9.' I'm afraid this was a bit of a *hareng rouge* ('red herring').

As we know, we currently have total control of all the segments. This means we can turn them all off before we modify the values on the inputs to our 2:4 decoder. When all the segments are off, it doesn't matter if we transition through intermediate input values or if the decoder's gate delays cause multiple transistors to be activated, because all we are displaying is… a blank. This means that if we were to add a 2:4 decoder to our current circuit, we would employ the sequence depicted in Fig.9e.

Now, you may be thinking that our rambling 2:4 decoder discussions serve no purpose, to which I would respond: (a) it's all curious James's fault for asking the question in the first place and (b) you may be surprised how the problems and solutions we've talked about here pop up again in the future.

What the heck!

I fear that I can no longer be trusted. Why? Well, earlier I said that we were just spitballing ideas and we weren't really going to deploy a 2:4 decoder. However, looking at Fig.12 has given me an uncontrollable urge to do just that.

I just glanced at my trusty *Texas Instruments TTL Data Book* (Second Edition) from 1981 – a classic, do yourself a favour and get one. The SN74139 is a 16-pin device containing two 2:4 decoders, and they even have enables if we wanted to use them, but they have active low outputs, which is opposite to what we want.

Also, it will be more fun to replicate the gate-level implementation shown in Fig.8c. To do this, we will need a hex inverter in the form of an SN7404 (Fig.13a) and a quadruple 2-input AND in the form of a SN7408 (Fig.13b). Both these devices are available in 14-pin breadboard-mountable dual in-line (DIL) packages. You can also access downloadable data sheets: 7404 (**https://bit.ly/44Rs3bb**) and 7408 (**https://bit.ly/3UwuCKV**) on the interweb.

You can order these chips individually if you wish, or you could opt for a small kit containing two each of the ten most popular 74LS devices, such as the Bridgold set on Amazon (**https://bit.ly/3wqgzyv**). Note that the 'LS' portion of their monikers stands for 'low-power Schottky,' but that's not something we need to concern ourselves with here.

The plastic packages typically have a small semicircular notch at one end between pins 1 and 14 as shown in Fig.13. Alternatively, they may have a dimple next to pin 1. Either way makes it easy to determine which pins are which.

Next, let's use the gate-level implementation from Fig.8c and our knowledge of the chip pins from Fig.13 to create a schematic (Fig.14).

It's common to use the character 'U' to indicate an integrated circuit in a schematic (we are saying that `U1` is our SN7404 and `U2` is our 7408). In the case of this sort of logic, sometimes we might show the entire package as a single symbol. Other times we may show the individual gates, in which case we add a number or letter to indicate which gate in the package we are talking about (eg, `U2.1` is the gate in the 7408 with signals `1A`, `1B`, and `1Y`; `U2.2` is the gate with signals `2A`, `2B`, and `2Y`; etc.). The pin numbers provide a further clue.

Now, let's add these devices to our breadboard-based clock (Fig.15) and wire them up as per our schematic (Fig.14). I've updated our master drawing to reflect these changes (file **CB-Jul24-02.pdf**). We will talk about the four unexpected resistors in a moment, but first…

Sometimes when you look at a gate-level schematic of a circuit board like

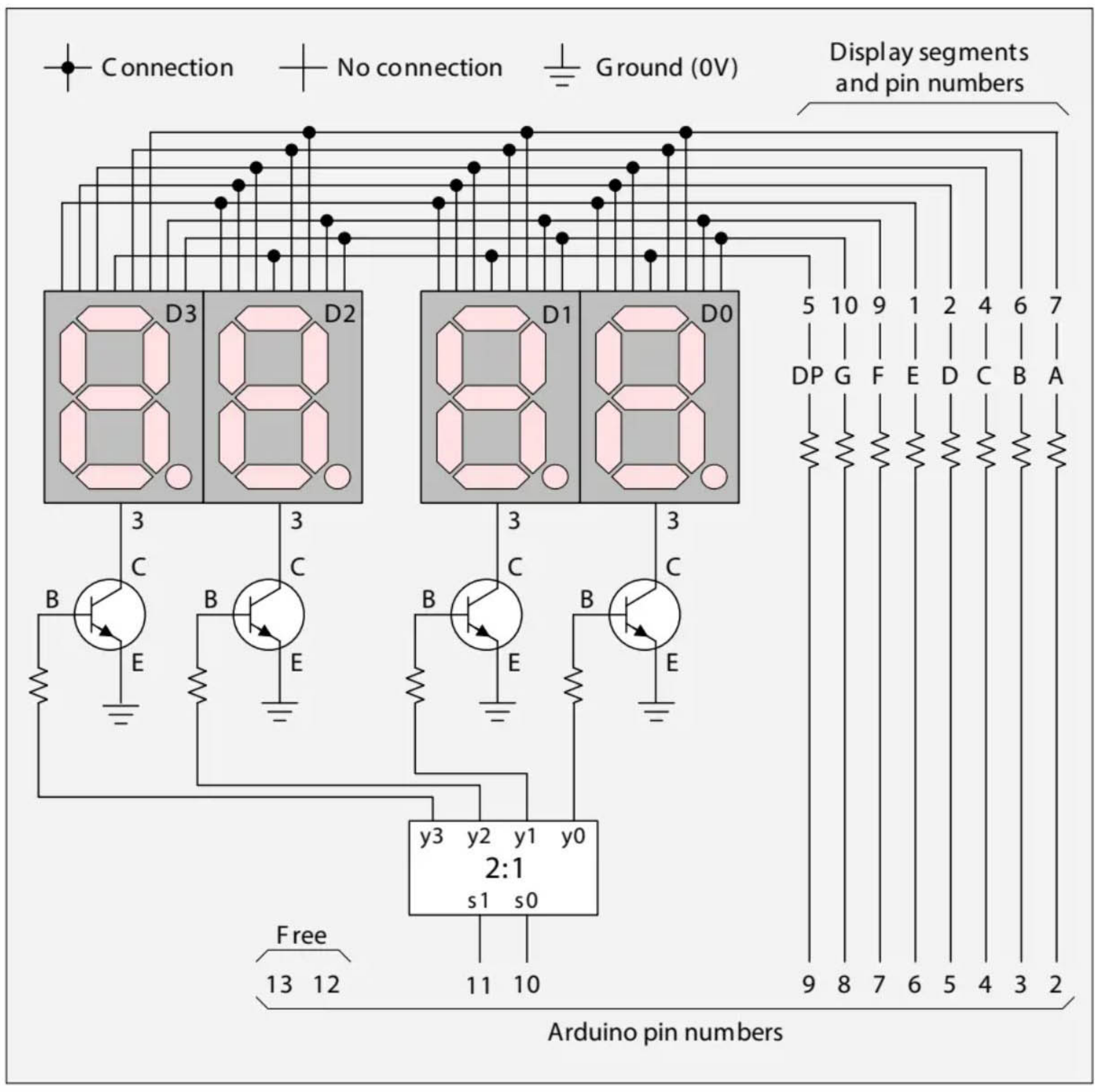


Fig.12. Current circuit augmented by 2:4 decoder.

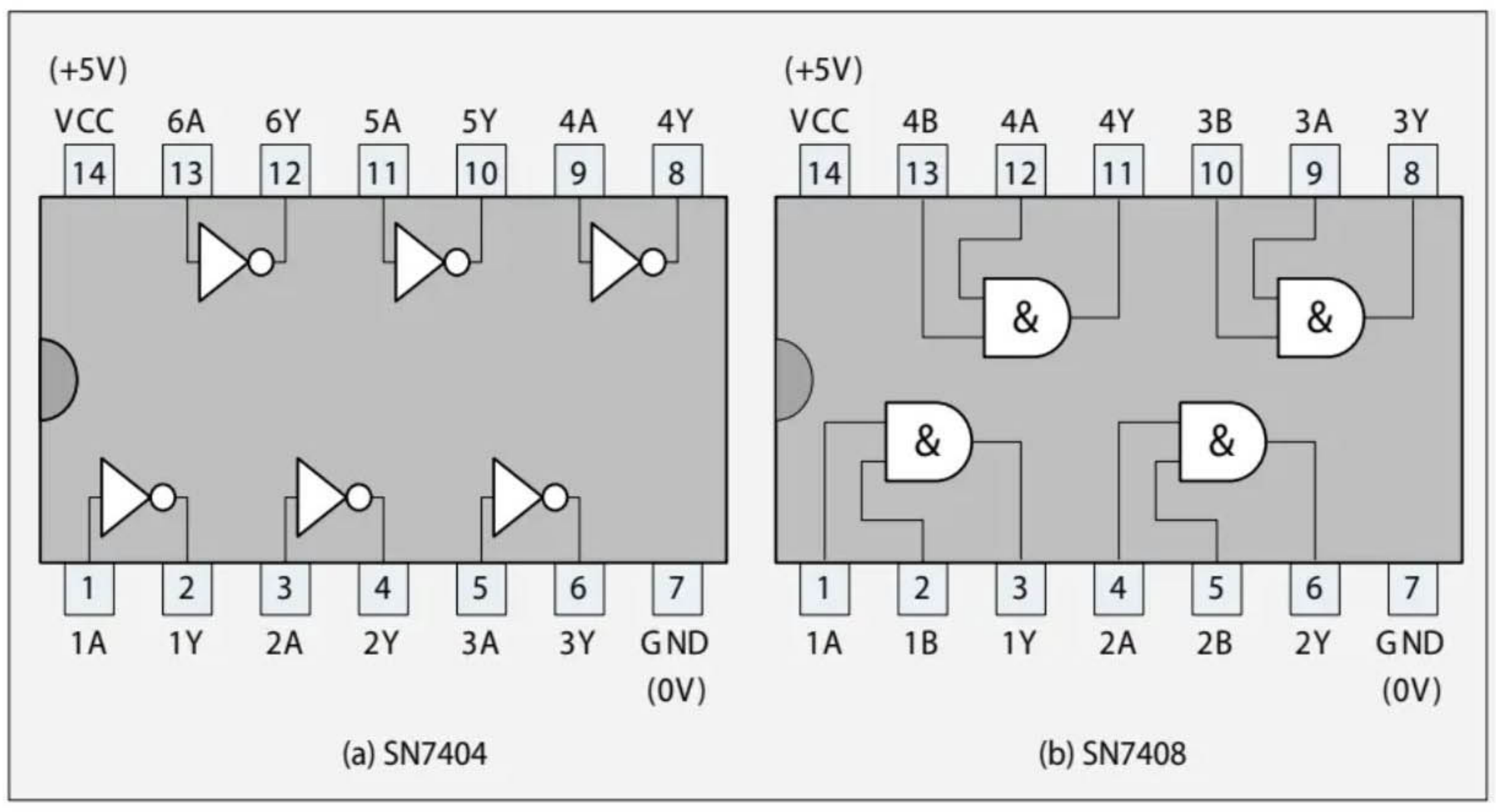
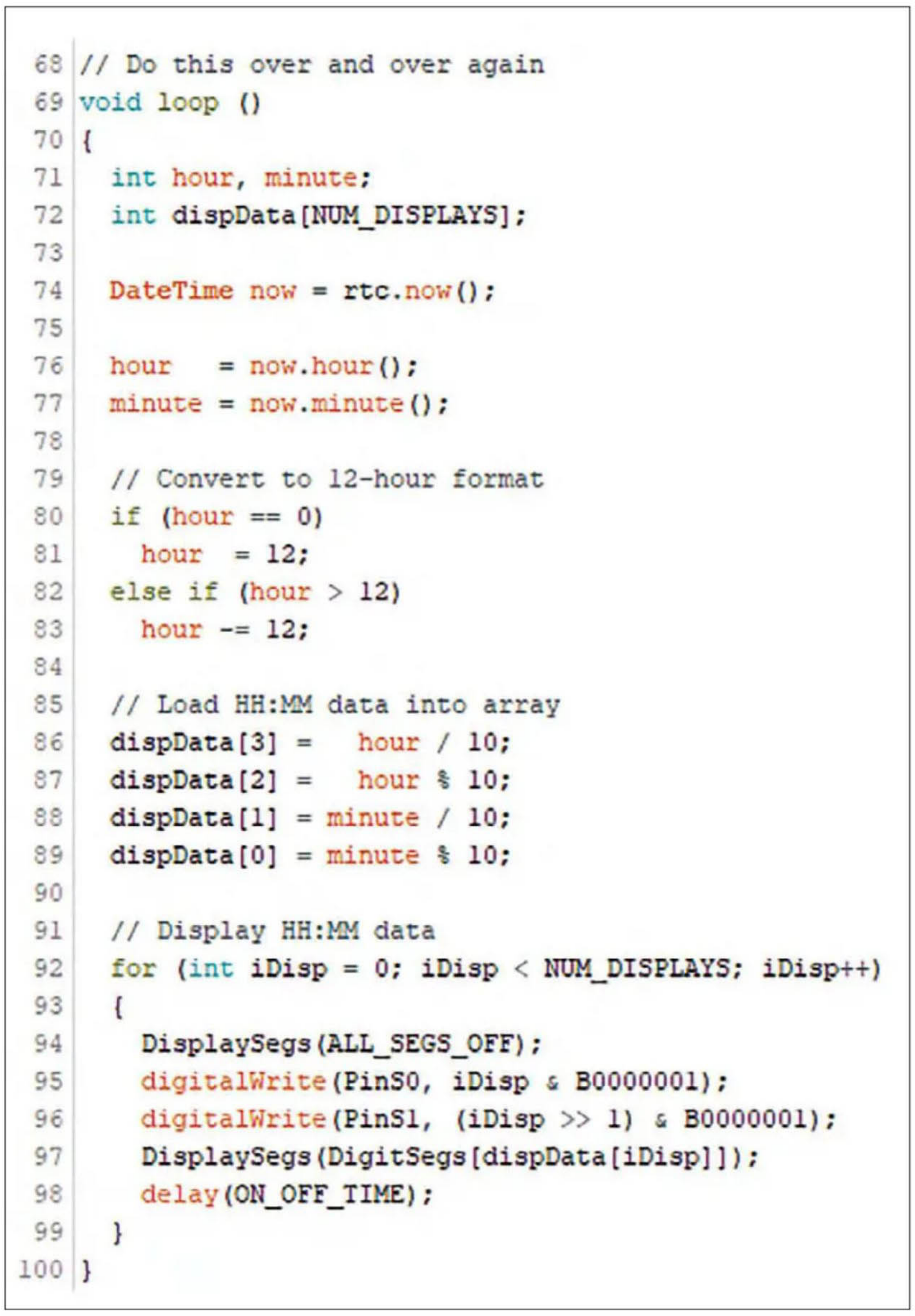


Fig.13. Chip packages.



```
// Do this over and over again
void loop ()
{
  int hour, minute;
  int dispData[NUM_DISPLAYS];

  DateTime now = rtc.now();

  hour   = now.hour();
  minute = now.minute();

  // Convert to 12-hour format
  if (hour == 0)
    hour  = 12;
  else if (hour > 12)
    hour -= 12;

  // Load HH:MM data into array
  dispData[3] =   hour / 10;
  dispData[2] =   hour % 10;
  dispData[1] = minute / 10;
  dispData[0] = minute % 10;

  // Display HH:MM data
  for (int iDisp = 0; iDisp < NUM_DISPLAYS; iDisp++)
  {
    DisplaySegs(ALL_SEGS_OFF);
    digitalWrite(PinS0, iDisp & B0000001);
    digitalWrite(PinS1, (iDisp >> 1) & B0000001);
    DisplaySegs(DigitSegs[dispData[iDisp]]);
    delay(ON_OFF_TIME);
  }
}
```

Listing 3a. Modifications to use 2:4 decoder.

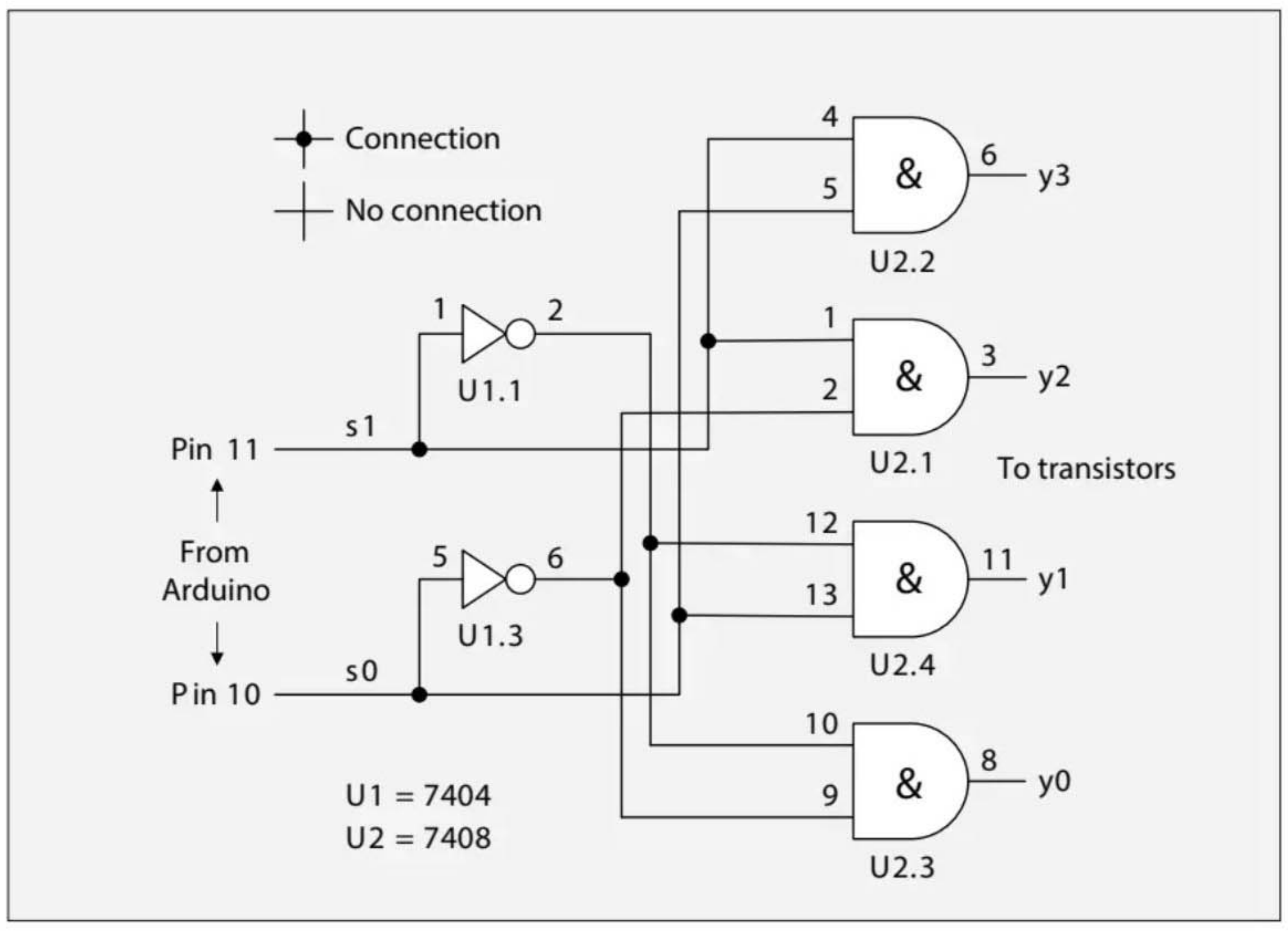


Fig.14. Gate-level schematic for 2:4 decoder.

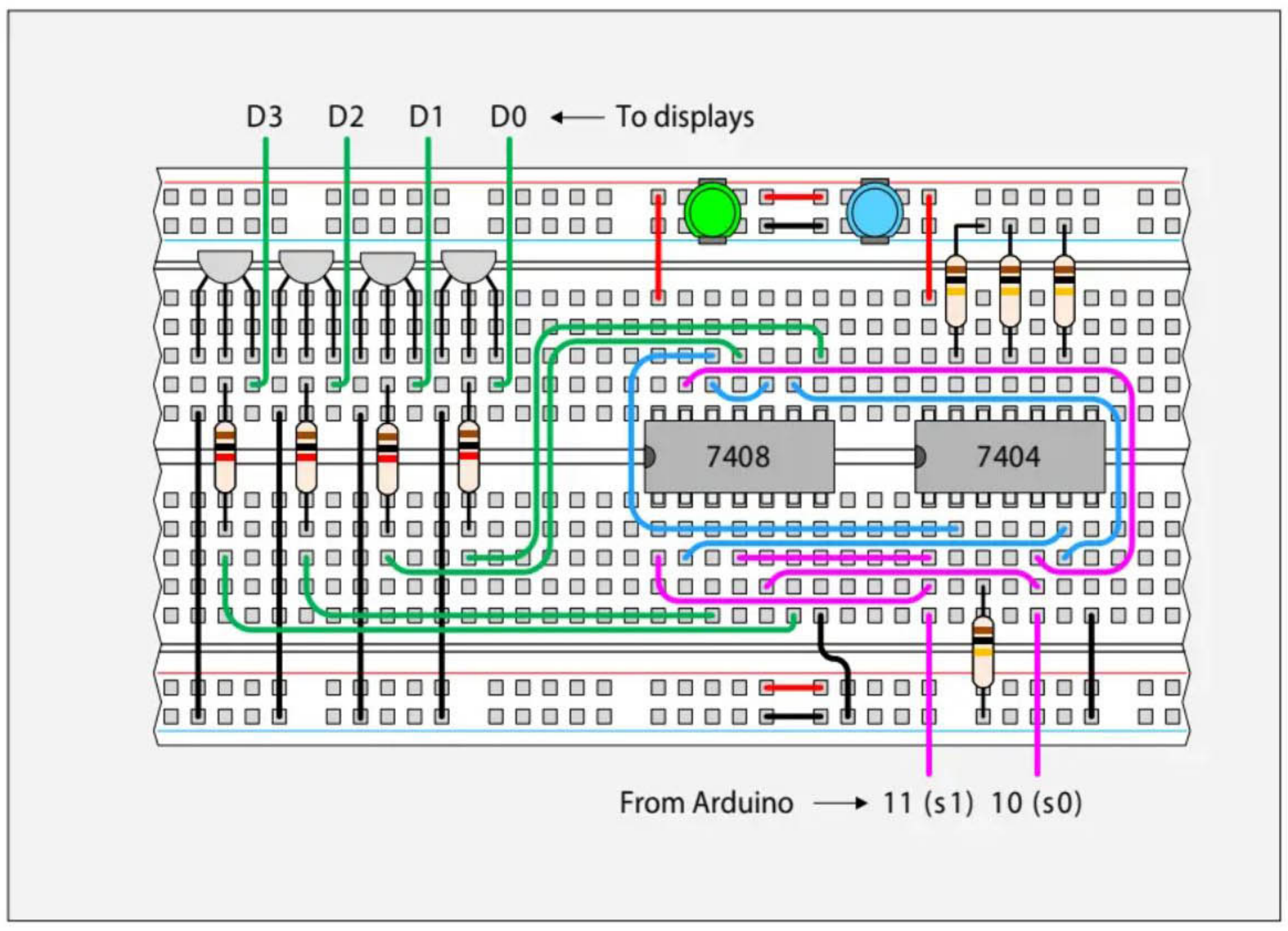


Fig.15. Wiring up the chips on the breadboard.

Fig.14, you wonder as to the rationale behind the way in which the designer selected which gates in which chips were to be connected to which wires. Why did I use `U2.3`, `U2.4`, `U2.1`, and `U2.2` to drive signals `y0`, `y1`, `y2`, and `y3`, respectively, for example?

Oftentimes, the answer is more pragmatic than you might expect – it facilitates the physical layout in some way. In this case, I wanted to be able to draw the wires associated with our chips in such a way that they didn't cross over, which would have made things harder for you to comprehend.

Feeling unconnected?

One final point worth noting before we fire up our new implementation is that we are using only two of the six inverters (NOT gates) in our SN74LS04 package. In a real-world design intended for production, we would typically use pull-up or pull-down resisters to connect any unused input pins to power or ground, respectively (Fig.16).

Why? Well, there's a faint possibility that an unconnected input, which may 'float' up and down, could result in that NOT gate undergoing uncontrolled oscillations, and an oscillating gate consumes power. Also, even though the outputs on our unused gates aren't connected to anything via wires, such oscillations may result in noise in the form of electromagnetic interference (EMI) that can affect other signals nearby.

Happily, the chances of this being a problem are extremely slight in our case, not least because of the SN74LSxx technology we are using. On the other hand, I'm trying to teach you good practices, and it's a good idea to get into the habit of tying off unconnected inputs, so that's what we are going to do.

In a scenario where gates are totally unused, as in our example, it's often up to the designer to decide between attaching pull-up or pull-down resistors to their inputs (remember that they are the same resistors; the 'up' and 'down' qualifiers are used to remind ourselves what we are doing with them). In this case, I favour using pull-down resistors to ground.

Also, it's usually the designer's choice as to the value of resistors to use. Anything 1kΩ or higher is typically good. I personally favour 10kΩ resistors (brown-black-orange). I have friends (seriously) who opt for 2.2kΩ (red-red-red) or 4.7kΩ (yellow-purple-red). In the case of a cheap-and-cheerful prototype, you may end up using whatever you have to hand.

In some situations, we may be using a gate or a more complex function, but not employing all its inputs. In such cases (unless stated otherwise in the data sheet), it's imperative that we apply appropriate resistors to place these pins in appropriate states. If we are using only two inputs to a 3-input AND gate, for example, we would use a pull-up resistor on the unused input (a pull-down would force the AND's output to

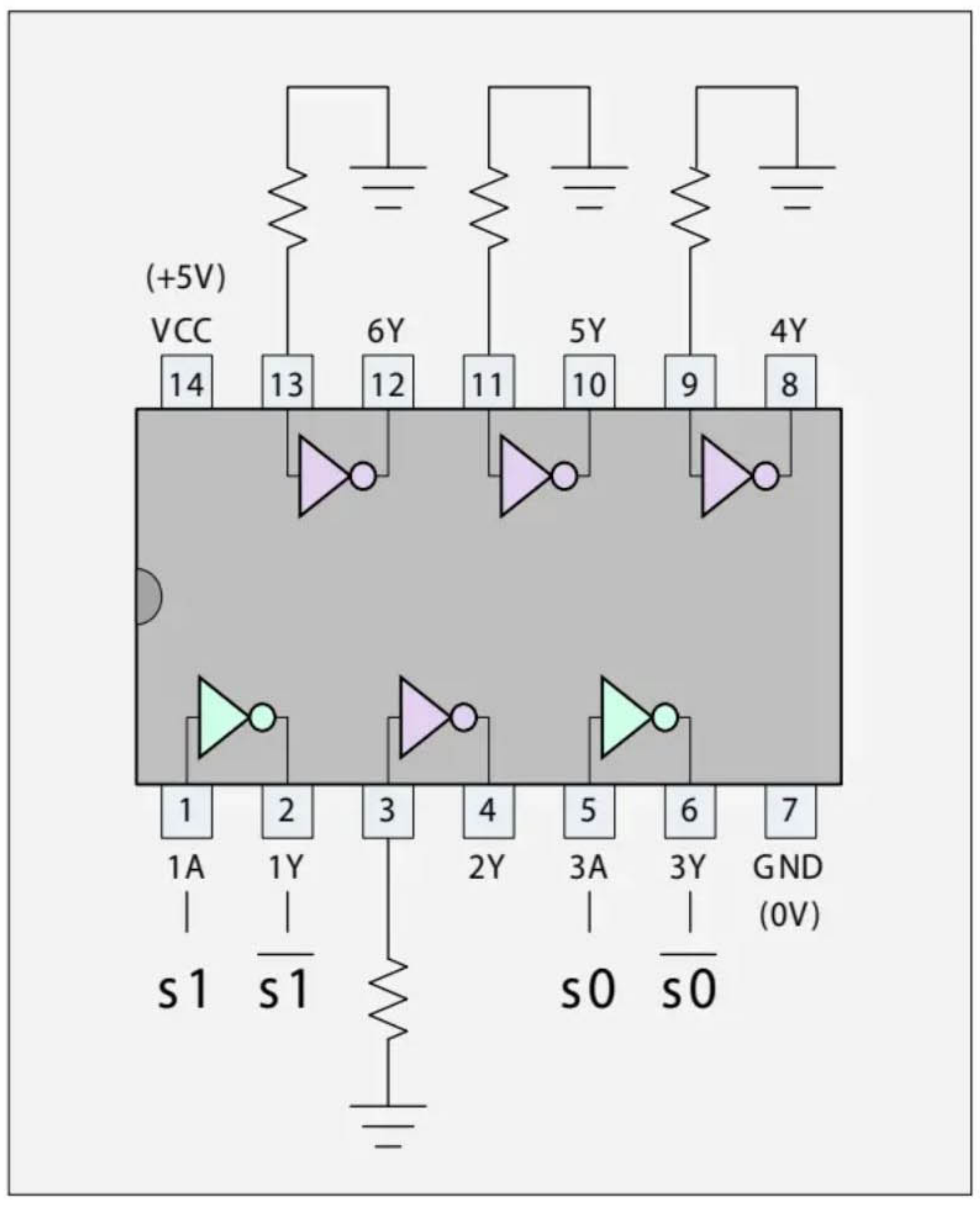


Fig.16. Unconnected inputs connected to ground via pull-down resistors.

0). Alternatively, if we are using only two inputs to a 3-input OR gate, we would use a pull-down resistor on the unused input (a pull-up would force the OR's output to 1).

Let's rock and roll!

I just forked the latest and greatest program from our previous column (*PE*, June 2024), edited it, and made it available for your perusing pleasure (file **CB-Jul24-03.txt**).

Let's skim through the minor changes before we look at the tasty part. We've removed our `TRAN_ON` and `TRAN_OFF` definitions because we are no longer driving the transistors directly. Similarly, we've replaced our `PinsTrans[]` array in which we specified the four pins used to drive our transistors with two independent definitions for our decoder select controls:

```
int PinS0 = 10;
int PinS1 = 11;
```

There are a few more minor tweaks of this ilk, but the big change takes place in our `loop()` function, as illustrated in Listing 3a.

To be honest, apart from the line numbers themselves, the statements associated with Lines 71 through 89 remain unchanged. The only new part takes place when we come to output our HH:MM data to the displays in Lines 92 through 99.

What we are doing is implementing the sequence shown in Fig.9e: Turn all segments off (Line 94) → Set 2:4 inputs (Lines 95 and 96) → Set new segment values (Line 97) → Delay 2ms (Line 98).

Most of this is achieved by reusing and reordering statements we've seen before. The only new part occurs on Lines 95 and 96 when we set the 2:4 input signals. To understand this, we first need to remind ourselves that we previously made the decision to activate our displays in the sequence D0, D1, D2, D3 (we could have done it the other way round, but this was easier).

To achieve this with our new circuit, we want the `s1-s0` signals driving the inputs to our 2:4 decoder to follow the sequence 00, 01, 10, 11 (Fig.8a, Fig.14, and Fig.15).

As part of our `for()` loop declaration on Line 92, our integer `iDisp` variable cycles through the values 0, 1, 2 and 3. In the case of the Arduino Uno, variables of type `int` (integer) are 16 bits wide. Let's consider the binary values of the least-significant eight bits in the context of our counting sequence (the most-significant eight bits will all be 0s).

iDisp		Binary
0	≡	00000000
1	≡	00000001
2	≡	00000010
3	≡	00000011

The math symbol ≡ means 'equivalent to' or 'identical to.' We discussed how to use the bitwise operators as masks in a previous Cool Beans (*PE*, March 2021). These are the techniques we are using here. Consider the following portion of Line 95:

```
iDisp & B0000001
```

Since we are using a bitwise `&` (AND) operator, any 0s in our Bxxxxxxxx value will return 0s in the corresponding positions in the result. By comparison, any 1s in our Bxxxxxxxx value will return whatever 0 or 1 value is in the corresponding bit of `iDisp` (note that this doesn't modify the contents of `iDisp` because we aren't assigning anything to `iDisp`).

Components from Part 1	
LEDs (assorted colours)	https://amzn.to/3E7VAQE
Resistors (assorted values)	https://amzn.to/3O4RvBt
Solderless breadboard	https://amzn.to/3O2L3e8
Multicore jumper wires (male-male)	https://amzn.to/3O4hnxk
Components from Part 2	
7-segment display(s)	https://amzn.to/3Afm8yu
Components from Part 5	
Momentary pushbutton switches	https://amzn.to/3Tk7Q87
Components from Part 6	
Passive piezoelectric buzzer	https://amzn.to/3KmxjcX
Components for Part 9	
SW-18010P vibration switch	https://bit.ly/46SfDA4
Components for Part 10	
Breadboard mounting trimpots	https://bit.ly/3QAuz04
Components for Part 12	
Light-Dependent Resistor	https://bit.ly/3S2430m
Components for Part 13	
BC337 NPN Transistor	https://bit.ly/40xAgyS
Components for Part 14	
HC-SR04 Ultrasonic Sensor	https://bit.ly/49AMBq4
Components for Part 15	
Real-Time Clock (RTC)	https://bit.ly/3S9OjHl
Components for Part 18	
Long tailed (0.1-inch pitch) header pins	https://bit.ly/3U1Vp2z
Components for Part 19	
Prototyping boards	https://bit.ly/3UMkcZ1
Kit of popular SN74LS00 chips	https://bit.ly/3wqgzyv

What this means is that this operation will return 00000000 (0) when `iDisp` is 0 or 2, and 00000001 (1) when `iDisp` is 1 or 3. Remembering that 0 and 1 are equivalent to `LOW` and `HIGH`, respectively, these are the values we are writing to our 2:4 decoder's `s0` input.

Now consider the following portion of Line 96:

```
(iDisp >> 1) & B0000001
```

This starts by using the `>>` bitwise shift right operator to shift the value from `iDisp` one bit to the right (again, this doesn't modify the value stored in `iDisp` because we aren't assigning anything to `iDisp`). The original least-significant bit 'falls off the end' and a 0 is shifted into the new most-significant bit. What this means is that, following the `>>` operation, we have the following intermediate value to play with:

iDisp		Binary after >> 1
0	≡	00000000
1	≡	00000000
2	≡	00000001
3	≡	00000001

When we subsequently perform the bitwise `&` (AND) operation, we will see 00000000 (0) when `iDisp` is 0 or 1, and 00000001 (1)

Cool bean Max Maxfield (Hawaiian shirt, on the right) is emperor of all he surveys at **CliveMaxfield.com** – the go-to site for the latest and greatest in technological geekdom.

Comments or questions? Email Max at: **max@CliveMaxfield.com** when `iDisp` is 2 or 3, and these are the values we are writing to our 2:4 decoder's `s1` input.

There are a couple of things to note here. The first is that the following two statement return identical results:

```
(iDisp >> 1) & B0000001
 iDisp >> 1  & B0000001
```

This is because the `>>` (bitwise shift) operator has a higher precedence than the `&` (bitwise AND) operator (for further details on this, I recommend *C/C++ Operator Precedence* at: **https://bit.ly/3wH8w06**). Personally, I prefer to use `( )` parentheses to (a) force the precedence I want and (b) to make it clear what I expect to occur to anyone reading my code (including me) in the future.

The second point is that we don't really need to perform the shift at all. For example, although the following statements return different results, these values will result in the same action in the context of our program:

```
(iDisp >> 1) & B0000001
 iDisp       & B0000010
```

This is because the `digitalWrite()` function will set the output to 0 (off, `LOW`) if it is presented with a value of 0 (zero), and it will set the output to 1 (on, `HIGH`) if it is presented with any other (non-zero) value of 1 or more.

I just ran our new program, and… ran into a WTW ('what the what?') problem with one of my breadboards. I'll tell you about this in my next column. Suffice it to say that, once I'd sorted my wayward breadboard, our 2:4 decoder-based clock performed like a dream (happy dance).

Online resources

For the purposes of this series, I'm going to assume that you are already familiar with fundamental concepts like voltage, current and resistance. If not, you might want to start by perusing and pondering a short series of articles I penned on these very topics – see: **https://bit.ly/3EguiJh**

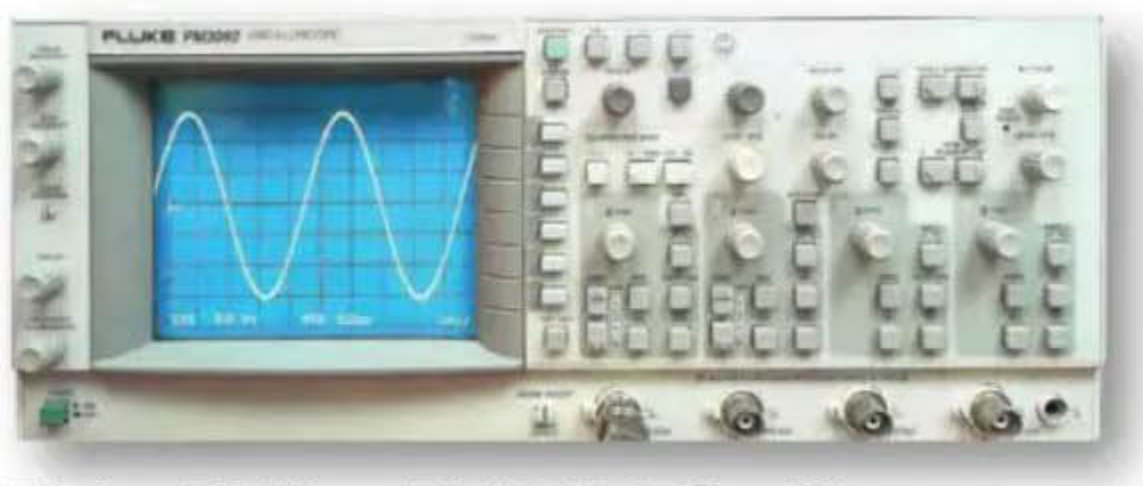
Similarly, I'll assume you are no stranger to solderless breadboards. Having said this, even if you've used these little scamps before, there are some aspects to them that can trap the unwary, so may I suggest you feast your orbs on a column I wrote just for you – see: **https://bit.ly/3NZ70uF**

Last, but not least, you will find a treasure trove of resources at the **Arduino.cc** website, including example programs and reference documentation.

Next time…

I'm afraid I've told two untruths (my mother won't be happy). As you may recall, at the end of our previous column, I said: 'In our next column, we really and truly are going to refresh our minds as to the concept of binary-coded decimal (BCD) and then investigate various deployments of BCD-to-7-segment decoders in our clock (otherwise my name's not *Max the Magnificent*).

The first untruth is that I failed in my BCD quest (we'll cover that next time). The second untruth is that my name is indeed *Max the Magnificent*, because that's what appears as my moniker on Zoom calls and name badges when I attend technical conferences, and you can't argue with logic like that! Until next time, have a good one!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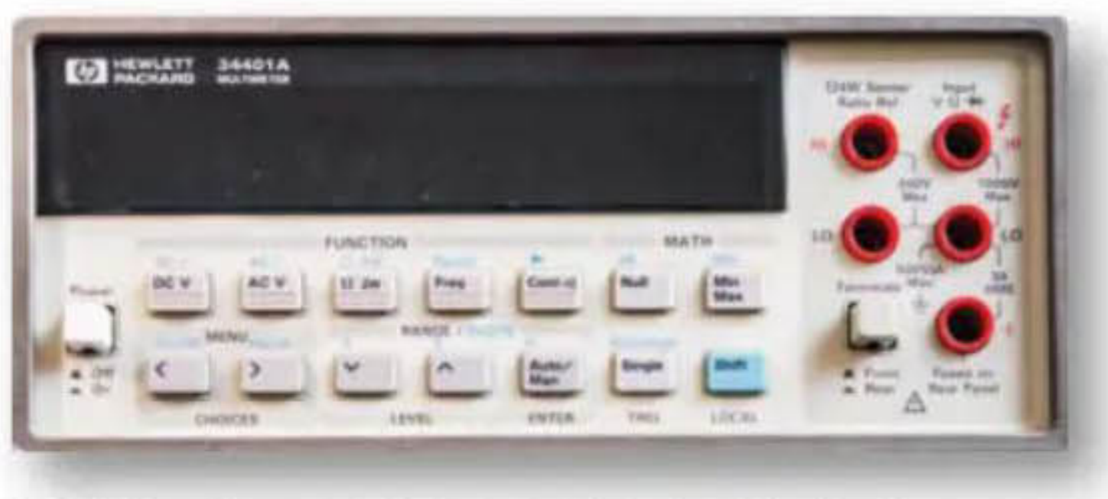
Tasakago TM035-2	PSU 0-35V 0-2A 2 Meters	£30
Thurlby PL320QMD	PSU 0-30V 0-2A Twice	£160 – £200
Thurlby TG210	Function Generator 0.002-2MHz TTL etc Kenwood Badged	£65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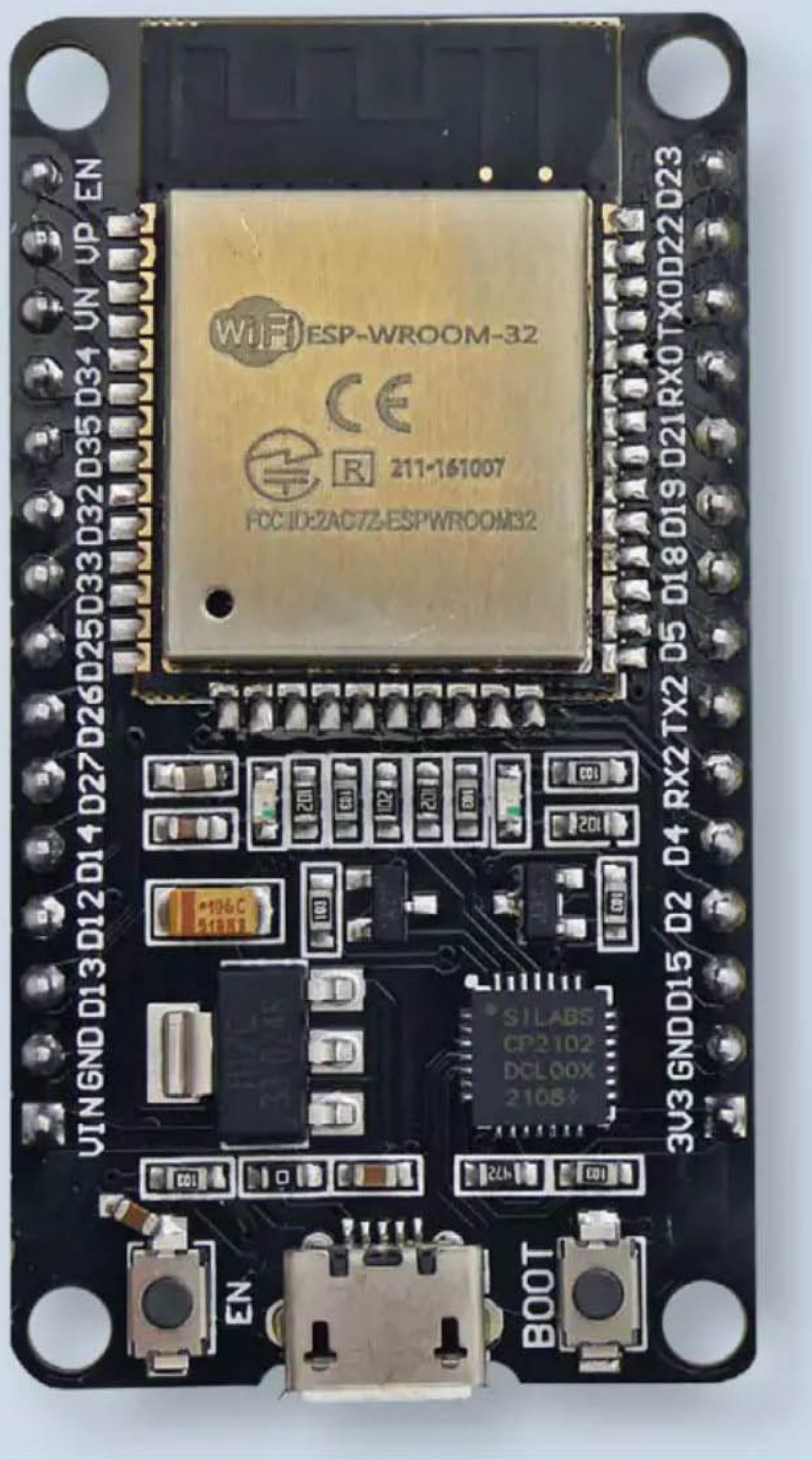
Teach-In 2024

Learn electronics with the ESP32

by Mike Tooley

Part 5 – Sensing the environment


ESP-WROOM-32
VIN GND D13 D12 D14 D27 D26 D25 D33 D32 D35 D34 VN VP EN
3V3 GND D15 D2 D4 RX2 TX2 D5 D18 D19 D21 RX0 TX0 D22 D23
EN
BOOT

In the previous part of our Teach-In series, we introduced seven-segment and matrix LED displays. We also introduced the SPI interface as a means of interfacing a wide variety of peripheral devices. *Coding Workshop* showed you how to generate and use random numbers and our *Teach-in Project* featured the design, construction and coding of a simple dice roller using a low-cost motion sensor as a trigger.

This month, we will introduce two more interface standards that simplify communication between the ESP32 and external hardware. We begin by introducing a range of low-cost temperature and humidity sensors that can be used in projects that need to sense conditions in the surrounding environment. *Coding Workshop* looks at maths operators and functions and our *Practical Project* shows how easy it is to add an LCD display to your designs.

The learning objectives for the fifth part of our series are know how to use:

- 1-wire and I2C interfaces to connect external hardware
- Temperature, humidity and other environmental sensors
- Low-cost I2C LCD displays.

The DHT22 temperature and humidity sensor

A variety of temperature and humidity sensors have become available for use in a wide range of situations where there is a need to sense, monitor and control the environment. Typical applications include heating, ventilation and air-conditioning (HVAC), dehumidifiers and humidity regulators, weather stations and data loggers, and vehicle environmental control.

We will start this part of *Teach-In* by introducing some popular temperature and humidity sensors, namely: the DHT11 (RHT01) and DHT22 (RHT02 or AM2302).

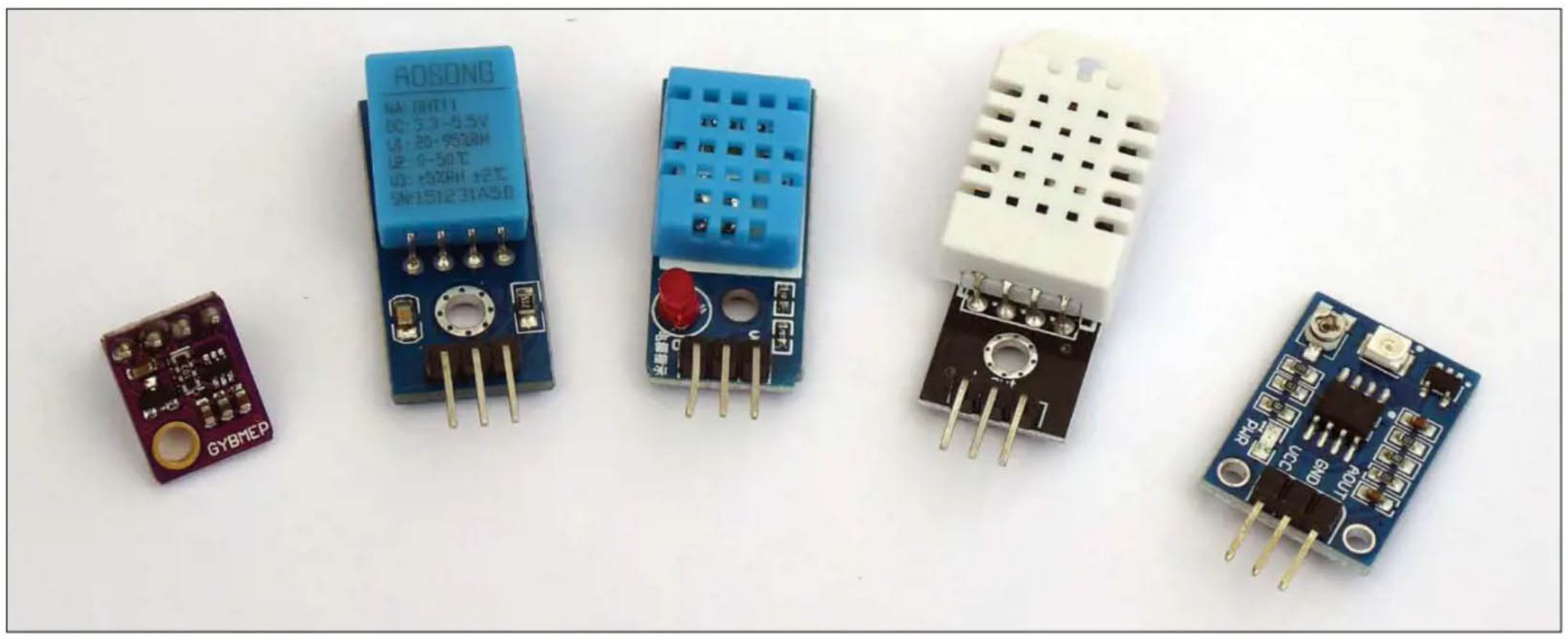


Fig.5.1. A wide variety of low-cost sensors are available for use with the ESP32. They include sensors for temperature, humidity, barometric pressure, and UV as well as the popular DHT11 and DHT22 types (centre).

About Teach-In

Our latest *Teach-In* series is about using the popular ESP32 module as a basis for learning electronics and coding. We will be making no assumptions about your coding ability or your previous experience of electronics. If you know one but not the other, you have come to the right place. On the other hand, if you happen to be a complete newbie there's no need to worry because the series will take a progressive hands-on approach. There will be plenty of time to build up your knowledge and plenty of opportunity to test things out along the way.

We've not included too much basic theory because this can be easily found elsewhere, including several of our previous *Teach-In* series, see:

https://bit.ly/pe-ti
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Earch month, there'll be projects and challenges to help you check and develop your understanding of the topics covered.

Unmounted DHT22 (and DHT11) sensors) are supplied in a 4-pin package. They are also available as small, printed circuit modules with a few additional components that enable them to be used in stand-alone applications where only three connections are required to a host microcontroller: positive supply, data and ground (negative supply).

The DHT devices use the 1-wire bus for communication between the sensor and a microcontroller. Sensed values of temperature and humidity are sent as serial data using the single wire connection. The sensor remains in a standby (low-power) mode until the host controller generates a start signal comprising a logic 0 (LOW) for at least 0.5ms, followed by a logic 1 (HIGH). When this signal is received, the sensor enters operational mode and responds with a serial stream comprising five bytes (40 bits) of data. This data consists of two bytes of RH data (high byte followed by low byte), two bytes of temperature data (high byte followed by low byte), and a checksum used to verify the data. A typical example of the serial data for a DHT22 sensor is shown in Table 5.1.

The checksum is found by adding the preceding four bytes of data. So, in

Table 5.1 Data format for a DHT22 sensor

Item	RH data (16 bits)	Temperature data (16 bits)	Checksum (8 bits)	HSPI pin no.
Binary data	`00000010 11101000`	`00000001 01101111`	`01011010`	14
Decimal equiv	744	367		13
Value indicated	74.4%	36.7°C		12

Table 5.2 Data format for a DHT11 sensor

Item	RH data (16 bits)	Temperature data (16 bits)	Checksum (8 bits)
Binary data	`00000000 01011001`	`00000000 00011001`	`01110010`
Decimal (×1)	89	25	
Value indicated	89%	25°C	

Check it out!

The 1-wire interface to a DHT22 (or similar) sensor is delightfully simple and requires just three connections, as shown in Fig.5.2. Asynchronous data is transferred via the ESP32's in-built universal asynchronous receiver transmitter (UART). This is often labelled 'RX2' on ESP32 development boards. Representative breadboard and wiring layouts are shown in Fig.5.3 and Fig.5.4.

this case, the checksum is determined as follows:

```
  0000 0010 (RH data high byte)
+ 1110 1000 (RH data low byte)
+ 0000 0001 (temp data high byte)
+ 0110 1111 (temp data low byte)
___________
  0101 1010 (checksum)
___________
```

Note that when the leading bit of the temperature data is set (ie, 1) this signifies a temperature below zero (ie, a negative temperature value). Note also that the data format used for the less accurate DHT11 sensor uses only the two low data bytes (the high bytes are all zero). The value of the low byte is decoded directly to produce integer values – see Table 5.2 for an example.

DHT11 and DHT22 (and equivalent) temperature and humidity sensors are laboratory calibrated and calibration data is stored in one-time programmable (OTP) memory. These sensors can be reliably used at distances of up to 20m from the host microcontroller.

For an overview of DHT11 and DHT22 specifications see Table 5.3.

Gotcha!

Take care when RH measurements are made in environments where airborne contaminants and gases are present.

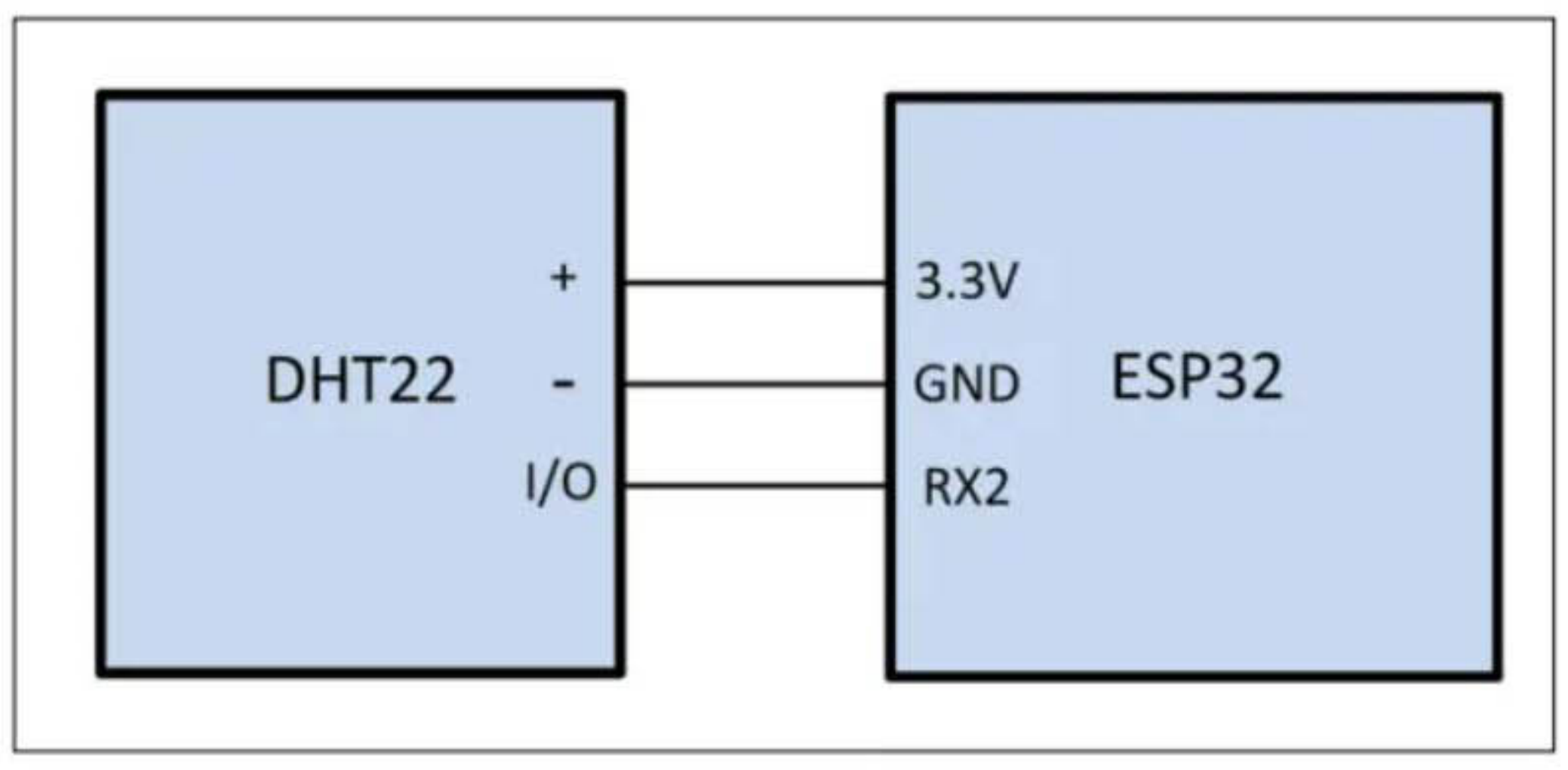


Fig.5.2. The minimal interconnection required to interface a DHT22 temperature and humidity sensor to an ESP32 development board (serial data is transferred using the ESP32's UART).

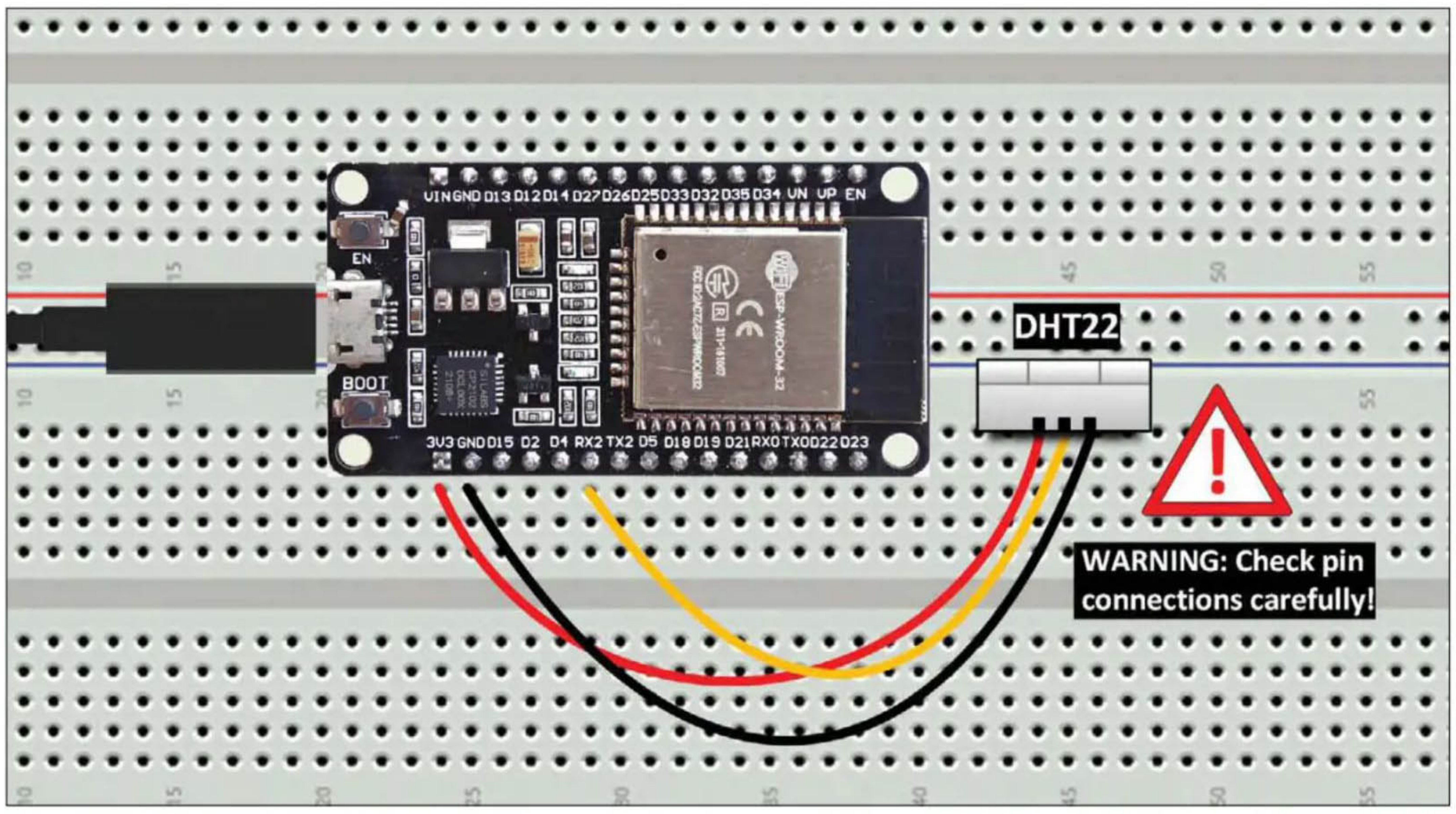


Fig.5.3. Breadboard layout for testing a DHT22 temperature and humidity sensor.

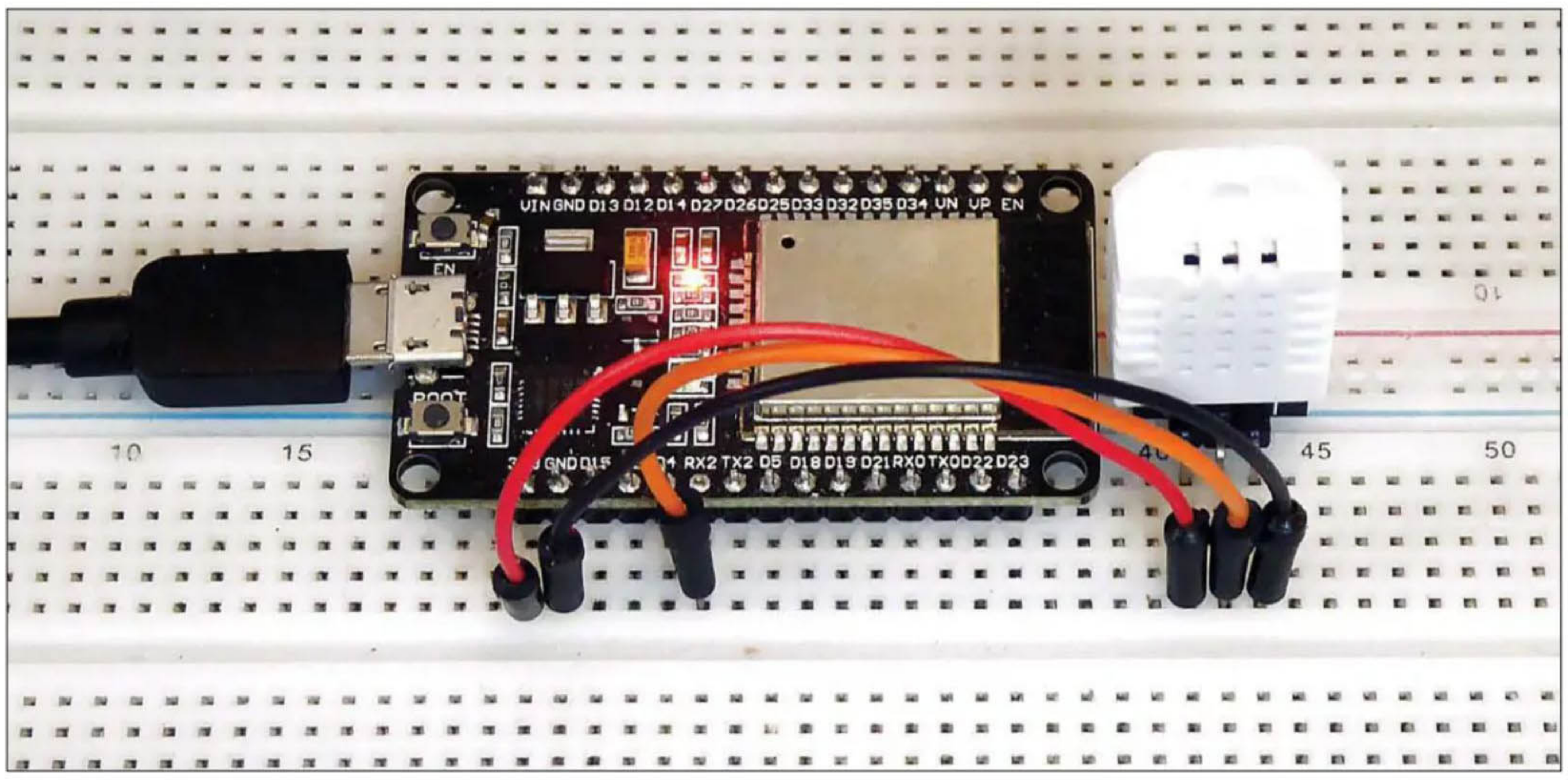


Fig.5.4. Breadboard wiring for the DHT22.

Table 5.3 DHT11 and DHT22 specifications

Characteristic	DHT11	DHT22
Characteristic	DHT11	DHT22
Temperature range	0 to +50°C	-40 to +80°C
Humidity range	20 to 90% RH	0 to 100% RH
Accuracy (temperature)	Better than ±2°C	Better than ±0.5°C
Accuracy (humidity)	Better than ±5% RH	Better than ±1% RH
Sensing period	1s (minimum)	2s (average)
Supply voltage	3 to 5.5V DC	3.3 to 6V DC
Supply current	2.5mA max. (150µA standby)	1.5mA max. (50µA standby)

Listing 5.1 Testing the DHT22 temperature and humidity sensor with an ESP32

```
/* ESP32 test with DHT22 sensor */

// Include the library file
#include <dhtnew.h>

DHTNEW mySensor(16);   // RX2 input

void setup()
{
   Serial.begin(115200);
   // Print headings
   Serial.print(“Temp.(C)”);
   Serial.println(“Humidity(%)”);
}

void loop()
{
   // Read the sensor and then display the data
   mySensor.read();
   Serial.print(mySensor.getTemperature(), 1);
   Serial.print(“\t”);
   Serial.println(mySensor.getHumidity(), 1);
   delay(5000); // Wait two seconds
}
```

Gotcha!

There's some variation in pin connections and marking on temperature and humidity modules. Some boards seem to have no pin markings at all. An inadvertent reverse supply connection can quickly destroy the sensor's 8-bit processor so it's important to check pin connections and wiring before applying power!

The code for testing the DHT22 is shown in Listing 5.1. Before executing the code you will need to use the IDE's Library Manager to locate and download the required library, `dhtnew.h`. We've included this library in our code using the following line:

```
#include <dhtnew.h>
```

The code in Listing 5.1 reads temperature and humidity data from the DHT22 module every four seconds. The data is then sent and displayed via the Serial Monitor. Fig.5.5 shows some typical data from the Serial Monitor.

A thermostatic controller

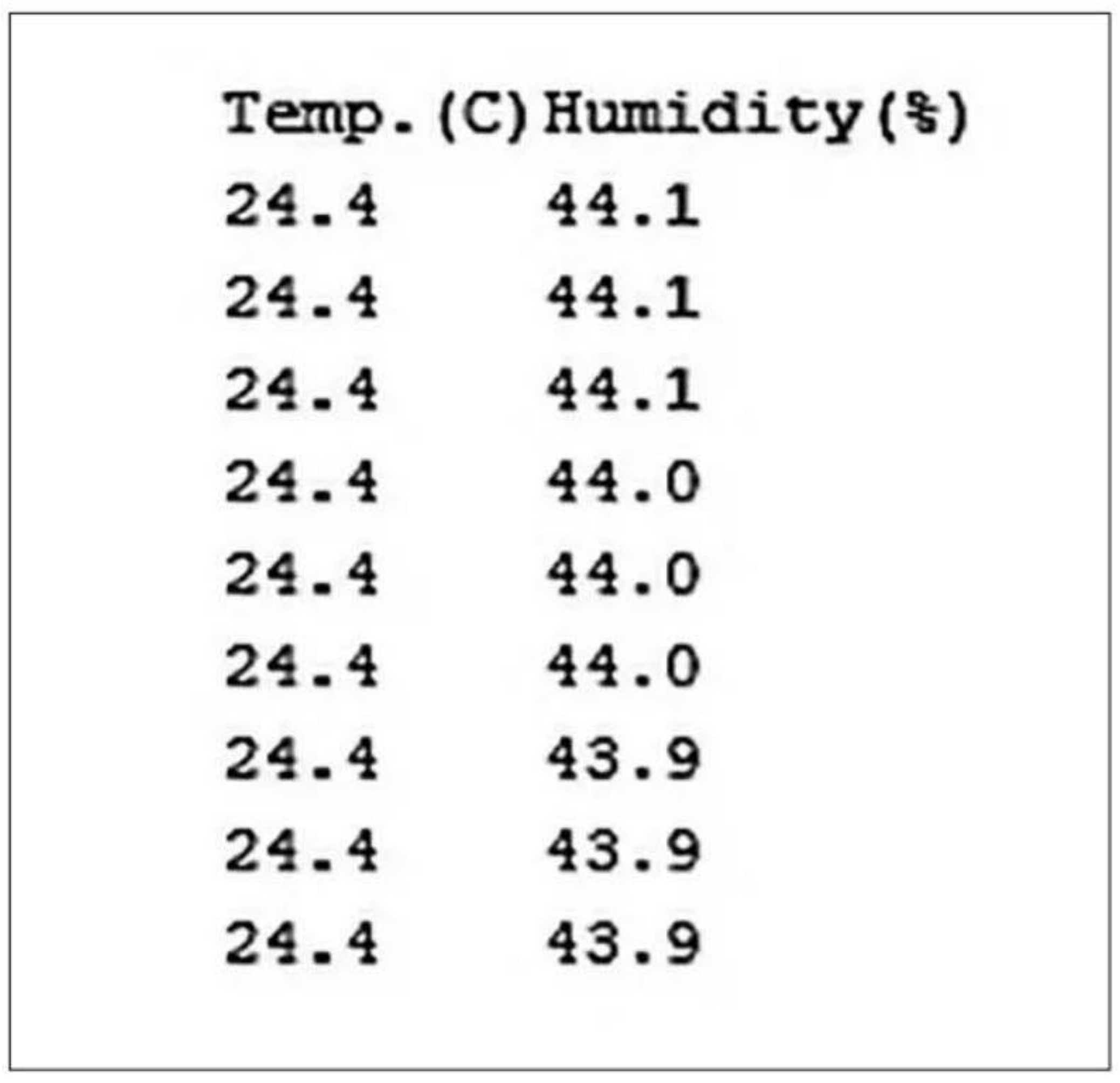
Now let's look at a practical application for a DHT sensor in the form of a simple greenhouse controller.

Since we don't need a high order of accuracy and wide temperature range, we will make use of a cheaper DHT11 sensor (see Table 5.3 for a comparison of these two sensors).

We will use the ESP32 to control two relays; one will operate a heater when the ambient temperature falls below a pre-determined level (the low threshold) and the other will operate a fan when the temperature exceeds a second pre-determined level (the high

Listing 5.2 Sample code for the thermostatic controller

```
/* ESP32 environmental controller
using a DHT11 temperature and humidity
sensor */

#include <dhtnew.h>  // Library file

// Define GPIO pins
const int HeaterRelay = 22;
const int FanRelay = 23;
int LowThreshold = 15;
int HighThreshold = 25;

DHTNEW mySensor(16);  // UART RXD input

void setup() {
   Serial.begin(115200);
   // Set relay pins as outputs
   pinMode(HeaterRelay, OUTPUT);
   pinMode(FanRelay, OUTPUT);
   // Initialise relays in off condition
   digitalWrite(HeaterRelay, HIGH);
   digitalWrite(FanRelay, HIGH);
}

void loop() {
   // First read the sensor
   mySensor.read();
   Serial.print(“Temperature: ”);
   Serial.print(mySensor.getTemperature(), 1);
   Serial.print(“ deg.C\t”);
   Serial.print(“Humidity: ”);
   Serial.print(mySensor.getHumidity(), 1);
   Serial.print(“ %\t”);
   // Then display the returned data
   if (mySensor.getTemperature() < LowThreshold) {
         digitalWrite(HeaterRelay, LOW);
         Serial.print(“Heat ON ”);
   } else {
         digitalWrite(HeaterRelay, HIGH);
         Serial.print(“Heat OFF ”);
   }
   if (mySensor.getTemperature() > HighThreshold) {
         digitalWrite(FanRelay, LOW);
         Serial.println(“Fan ON ”);
   } else {
         digitalWrite(FanRelay, HIGH);
         Serial.println(“Fan OFF ”);
   }

   delay(1000);  // Wait for 1 second
}
```



```
Temp.(C)Humidity(%)
24.4    44.1
24.4    44.1
24.4    44.1
24.4    44.0
24.4    44.0
24.4    44.0
24.4    43.9
24.4    43.9
24.4    43.9
```

Fig.5.5. Typical Serial Monitor data values obtained from Listing 5.1.

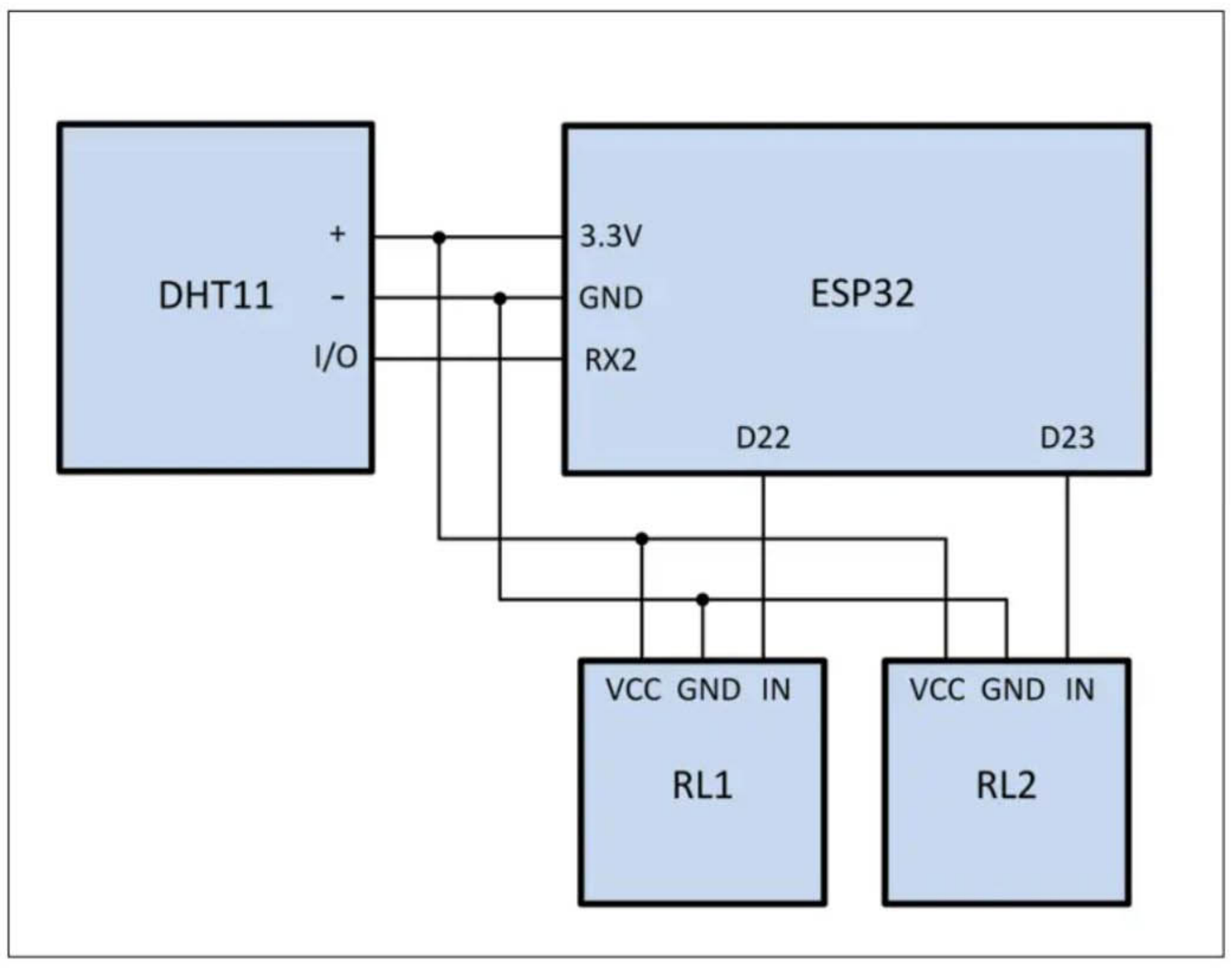


Fig.5.6. Circuit for the ESP32 thermostatic controller.

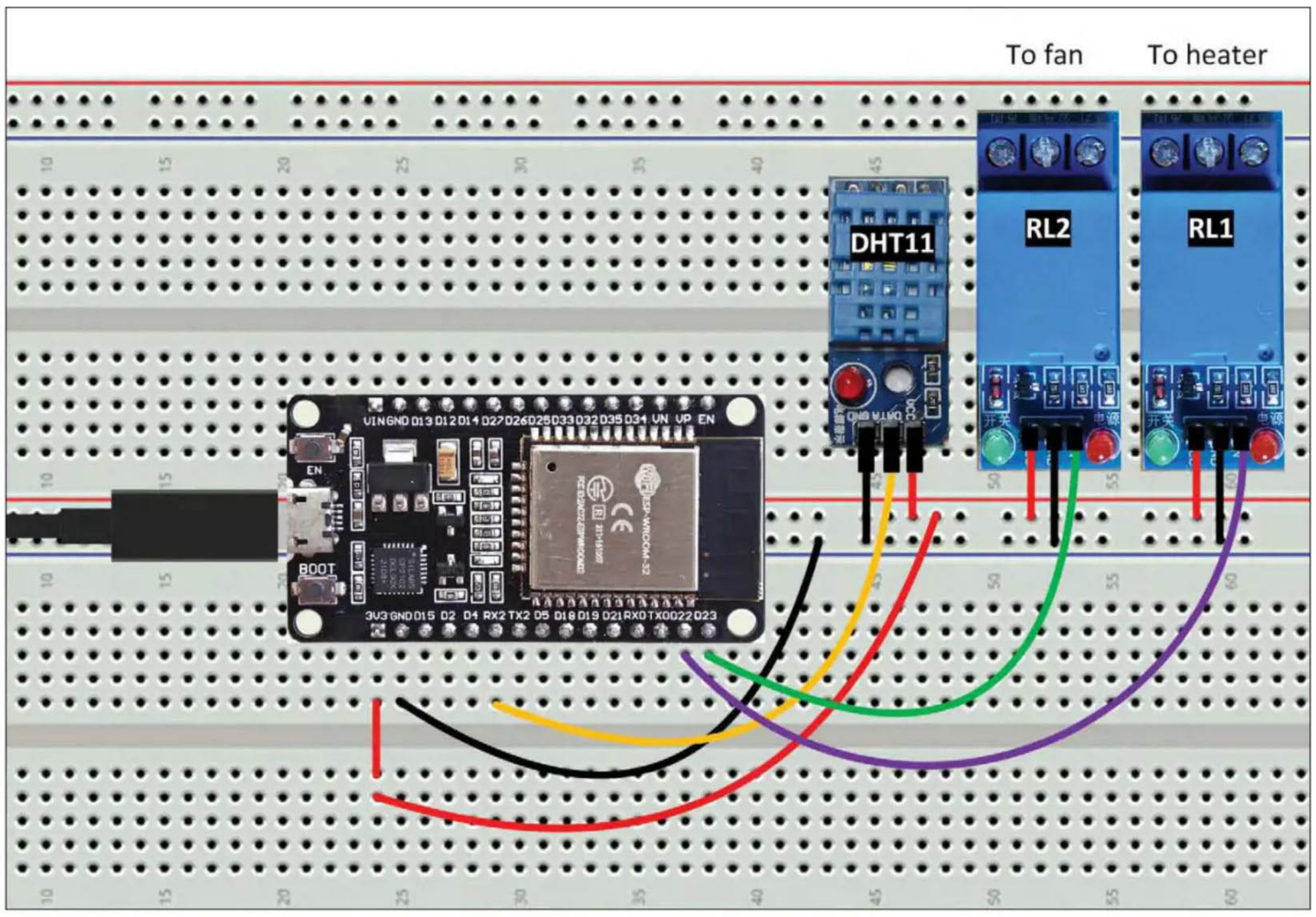


Fig.5.7. Breadboard layout for the ESP32 thermostatic controller.

threshold). The aim of the thermostatic controller is to maintain the environment's ambient temperature within a range bounded by the two thresholds.

The circuit of the ESP32 thermostatic controller is shown in Fig.5.6. The relay modules are interfaced to the ESP32 using GPIO pins initialised for digital operation (see *Teach-In Part 2* for further information). The DHT11 sensor module is connected, as before, using the 1-wire interface.

A representative breadboard layout is shown in Fig.5.7 and a practical wiring arrangement in Fig.5.8. Note that, to simplify interconnection and aid prototype manufacture, we've used a popular low-cost ESP32 expansion board in this arrangement. Expansion boards are relatively inexpensive and can be particularly useful as an interim stage between breadboard and final PCB layout.

Sample code for the thermostatic controller is shown in Listing 5.2. You should have already located and installed the required library file (see earlier). For test purposes, we've included status messages for the Serial Monitor. These, together with the LED indicators on the two relay modules, will allow you to confirm operation of the controller. Notice that we've defined the low threshold as 15°C and the high threshold as 25°C (a target temperature range of 10°C). These values can of course be changed to suit individual requirements.

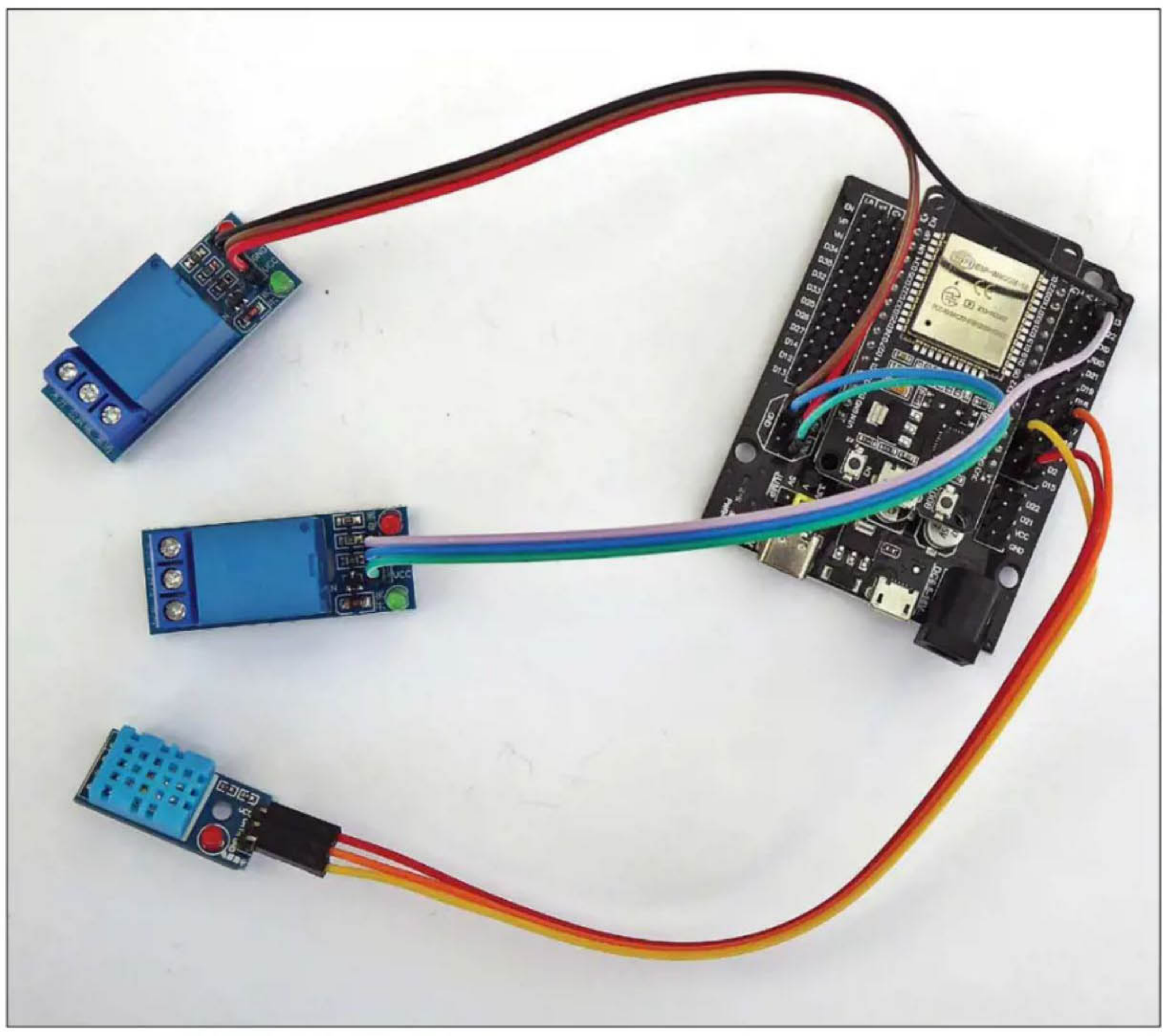


Fig.5.8. Wiring for the thermostatic controller based on a popular ESP32 expansion board.

The I2C bus

In *Teach-In Part 4* we showed how the serial peripheral interface bus (SPI) allows you to connect a wide variety of external devices to an ESP32. In addition to SPI, the ESP32 supports another useful method of connecting to the outside world using the 'Inter-Integrated Circuit' interface (abbreviated variously to IIC, I2C, I^{2}C (spoken 'I-squared-C'). This is a good point to introduce I2C as we will shortly be using it to attach a low-cost LCD panel to display your temperature and humidity data.

I2C is a simple bus system in which bidirectional data appears on a single line (SDA) and a clock signal is sent on a second bus line (SCL). Contrast this with SPI, which offers a point-to-point connection where data is passed in and out on separate lines (MOSI and MISO). SPI is faster and generally easier to use than I2C but there are many situations in which I2C is preferred simply because the interface is built into the chip that you need to use.

I2C was the brainchild of Philips, but several of its competitors (including Motorola/Freescale, NEC, Siemens, STM and Texas Instruments) have developed their own I2C compatible products. In addition, Intel's SMBus provides a stricter definition of I2C intended to improve the interoperability of I2C devices from different manufacturers.

A representative SPI bus arrangement is illustrated in Fig.5.9. Note that this system comprises two bus masters and three bus slaves. A microcontroller (eg, an ESP32) takes the role of master, while devices such as sensors and displays assume the role of slave.

Since the data line (SDA) is shared between multiple devices, I2C needs a system of addressing to identify the device that it needs to communicate with. Communication is initiated by means of a unique start sequence which involves pulling the data line (SDA) low while the clock line (SCL) is high. This can be achieved by using very simple bus interface logic where each of the bus lines are normally pulled high and driven low when activated by a device connected to the bus (see Fig.5.10).

Following the start sequence, transmitted data is only allowed to change when the clock is in its low state. In its basic form, and by virtue of the seven bits available for addressing, the I2C protocol caters for a total of 127 devices. In addition to the seven bits used for addressing, the first byte of an I2C transfer generated by a 'master' includes a bit that indicates the

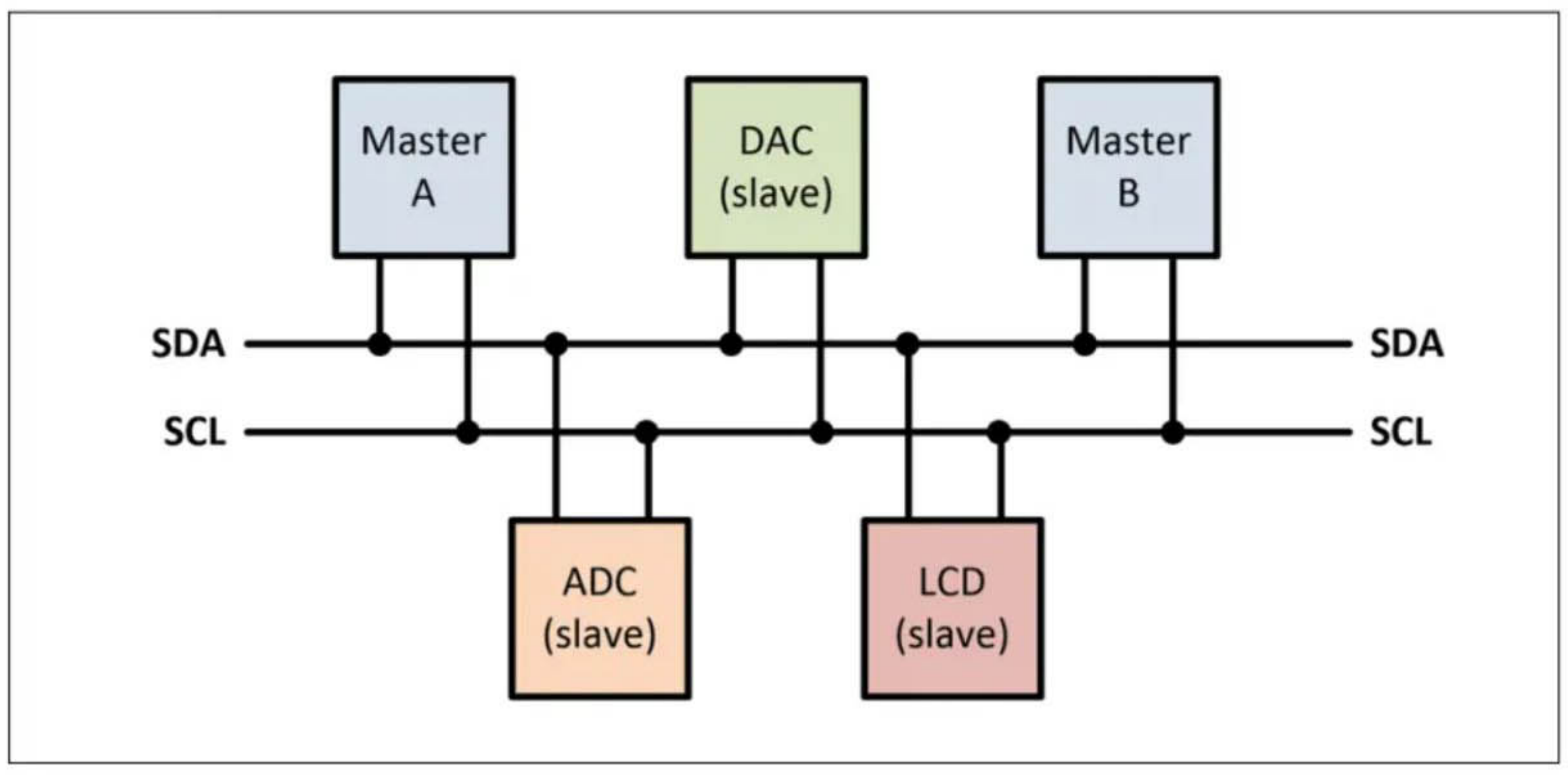


Fig.5.9. A representative I2C bus with two bus masters and three slaves present.

Table 5.4 A selection of common I2C devices

Device	Application	Manufacturer	I2C address
ADS1015	4-channel 12-bit ADC	Texas Instruments	0x2c to 0x2f
ADS1115	4-channel 16-bit ADC	Texas Instruments	0x48 to 0x4b
ADXL345	3-axis accelerometer	Analog Devices	0x1d, 0x53
AHT10	Temperature and humidity sensor	Asair	0x38
AHT20	Temperature and humidity sensor	Asair	0x38
BMA180	Accelerometer	Bosch	0x77
BME280	Temperature, pressure and humidity sensor	Bosch	0x76, 0x77
BMP085	Barometric pressure sensor	Bosch	0x77
BMP180	Temperature/barometric pressure sensor	Bosch	0x76, 0x77
BMP280	Temperature/barometric pressure sensor	Bosch	0x77
CCS811	Gas and air quality sensor	ScioSense	0x5a, 0x5b
D7S	Vibration sensor	Omron	0x55
DS1307	Real-time clock	Maxim	0x68
FS3000	Air velocity sensor	Renesas	0x28
HT16K33	LED matrix driver	Holtek	0x70 to 0x77
ITG3200	3-axis gyro	InvenSense	0x68, 0x69
LTC4151	Voltage and current monitor	ST Microelectronics	0x66 to 0x6f
MAX44009	Ambient light sensor	Maxim	0x4a, 0x4b
MCP23017	I2C GPIO expander	Microchip	0x20 to 0x27
MCP4728	4-channel 13-bit DAC	Microchip	0x60 to 0x67
MPR121	12-point capacitive touch sensor	NXP	0x5a to 0x5d
SAA1064	4-digit LED driver	NXP	0x38 to 0x3b
TDA8421	Audio processor	NXP	0x40, 0x41
TEA5767	Radio receiver	NXP	0x60
TSL2561	Light sensor	Texas Instruments	0x39, 0x49
VML6075	UV sensor	Vishay	0x10

direction of the data transfer. The address is transferred with the most-significant bit first (see Fig.5.11). Table 5.4 lists just a small selection of currently available devices that support I2C.

What's connected?

It's useful to have a means of determining how many I2C devices are present in a system as well as which I2C addresses have been allocated. This is achieved using an application known as an 'I2C scanner' along the lines of that shown in Listing 5.3. (Fig.5.12 shows some typical data from the I2C scanner.) Note that I2C applications require the `Wire.h` (or equivalent) library and so we've included it (using `#include`) at the start of the code.

Practical Project

Now let's move on with an I2C application that will send temperature and humidity data from a DHT22 sensor to a low-cost LCD panel. With only two GPIO pins needed for data transfer this leaves plenty of I/O available for use with other items of external hardware.

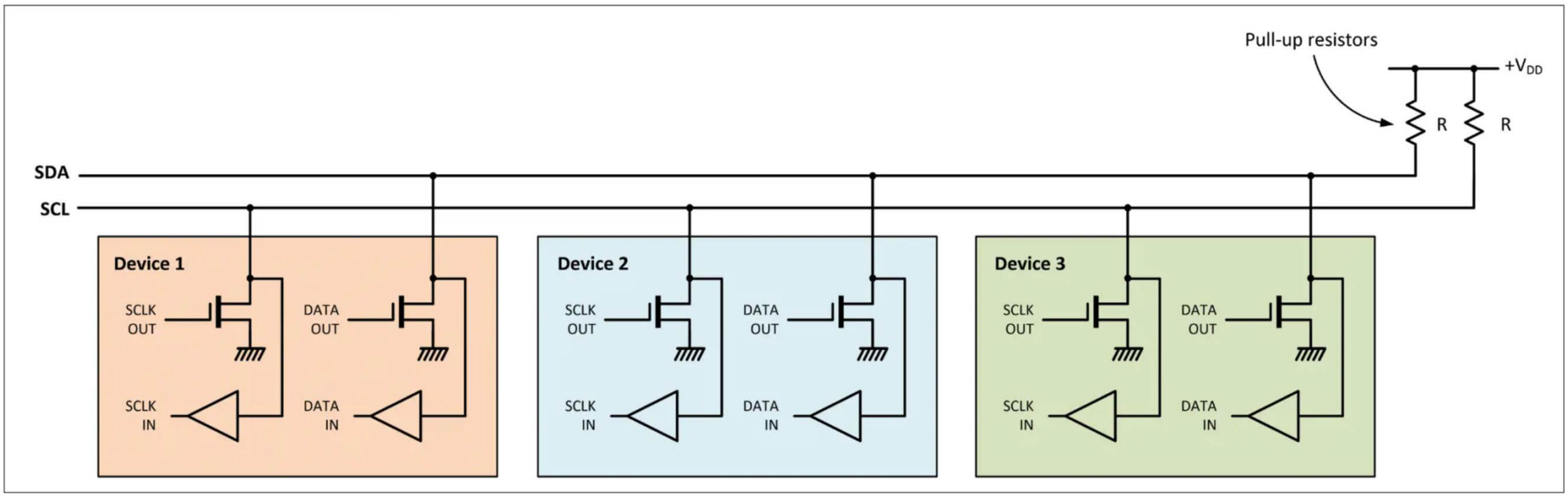


Fig.5.10. I2C bus interface logic.

Listing 5.3 A simple I2C scanner

```
/* Simple I2C scanner */

#include <Wire.h>

void setup() {
   Serial.begin (115200);
   Serial.println ();
   Serial.println (“Performing I2C scan ...”);
   byte count = 0;

   Wire.begin();
   for (byte i = 8; i < 120; i++)
   {
     Wire.beginTransmission (i);
     if (Wire.endTransmission () == 0)
          {
          Serial.print (“I2C device found at: “);
          Serial.print (“ 0x”);
          Serial.println (i, HEX);
          count++;
          }
   }
// Scan complete so print total found
   Serial.print (“Scan completed. Found “);
   Serial.print (count, DEC);
   Serial.println (“ device(s).”);
}

void loop() {
// Main code (if any) goes here
}
```

Listing 5.4 Sample code for the LCD temperature and humidity monitor

```
* ESP32 with DHT22 and 16 x 2 LCD
to display temperature and humidity */

// Include the library files
#include <dhtnew.h>
#include <LiquidCrystal_I2C.h>
// Define the LCD parameters
int lcdColumns = 16;
int lcdRows = 2;
// Setup the LCD
LiquidCrystal_I2C lcd(0x27, lcdColumns, lcdRows);
DHTNEW mySensor(16);  // UART RXD input

void setup() {
   Serial.begin(115200);
   // Initialize LCD
   lcd.init();
   // Turn the backlight ‘on’
   lcd.backlight();
}

void loop() {
   // First read the sensor
   mySensor.read();
   // Now display on the LCD
   lcd.setCursor(0, 0); // First row
   lcd.print(“Temp: “);
   lcd.print(mySensor.getTemperature(), 1);
   lcd.print(“ deg.C”);
   lcd.setCursor(0, 1); // Second row
   lcd.print(“Humidity:  “);
   lcd.print(mySensor.getHumidity(), 1);
   lcd.print(“%”);
   delay(5000);  // Wait for 5 seconds
   lcd.clear();
}
```

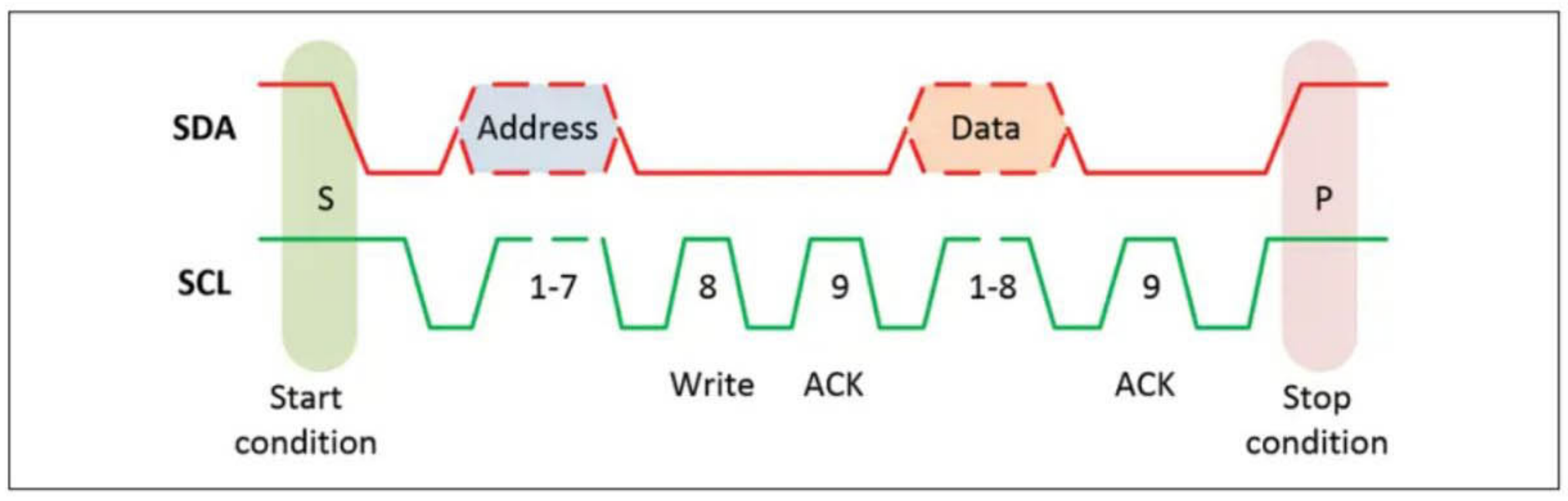
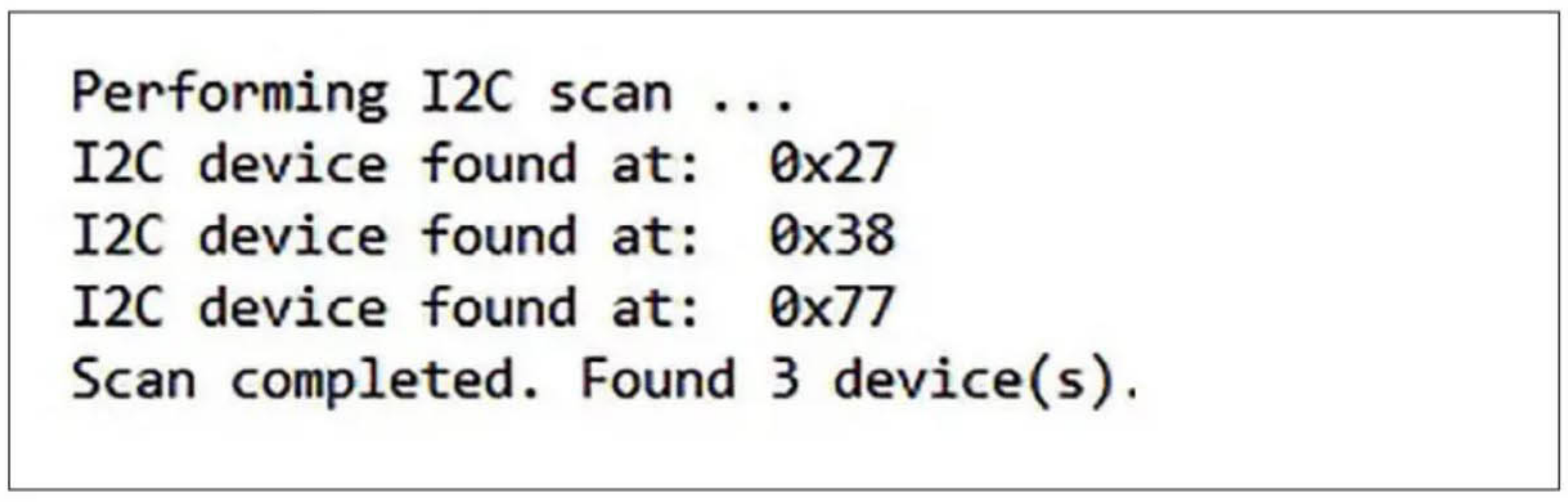


Fig.5.11. I2C bus transaction showing how first an address and then data is placed on the bus.



```
Performing I2C scan ...
I2C device found at:  0x27
I2C device found at:  0x38
I2C device found at:  0x77
Scan completed. Found 3 device(s).
```

Fig.5.12. Typical Serial Monitor output when using the I2C scanner in Listing 5.3.

The circuit arrangement for the LCD and DHT22 application is shown in Fig.5.13. This arrangement is based on a low-cost 16 × 2 LCD panel fitted with an I2C interface (see Fig.5.14). Note that the interface is mounted on the back of the LCD panel and has four connections: GND, VCC, SDA and SCL. SDA is used for data and SCL is used for the clock signal.

With the code in Listing 5.4 running, the breadboard wiring for the LCD and DHT22 application is shown in Fig.5.15. If required, the display backlight can be adjusted using the small preset resistor (the square blue component shown in Fig.5.14).

You should notice that we’ve included two libraries at the beginning of the code in Listing 5.4 using these lines:

```
#include <dhtnew.h>  // To use the DHTxx sensor
#include <LiquidCrystal_I2C.h> // To use the LCD
```

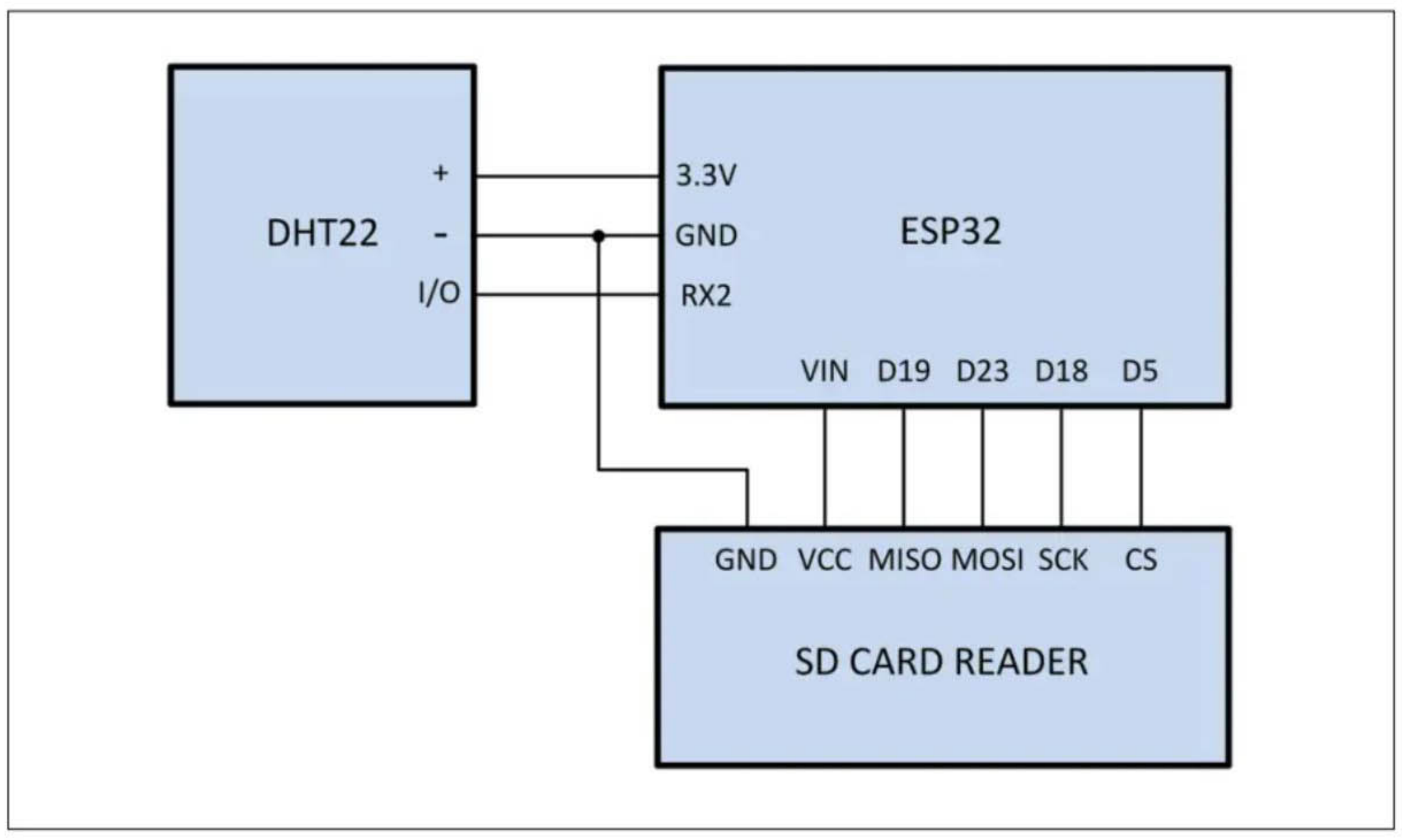


Fig.5.13. Circuit arrangement for the LCD and DHT22 application.

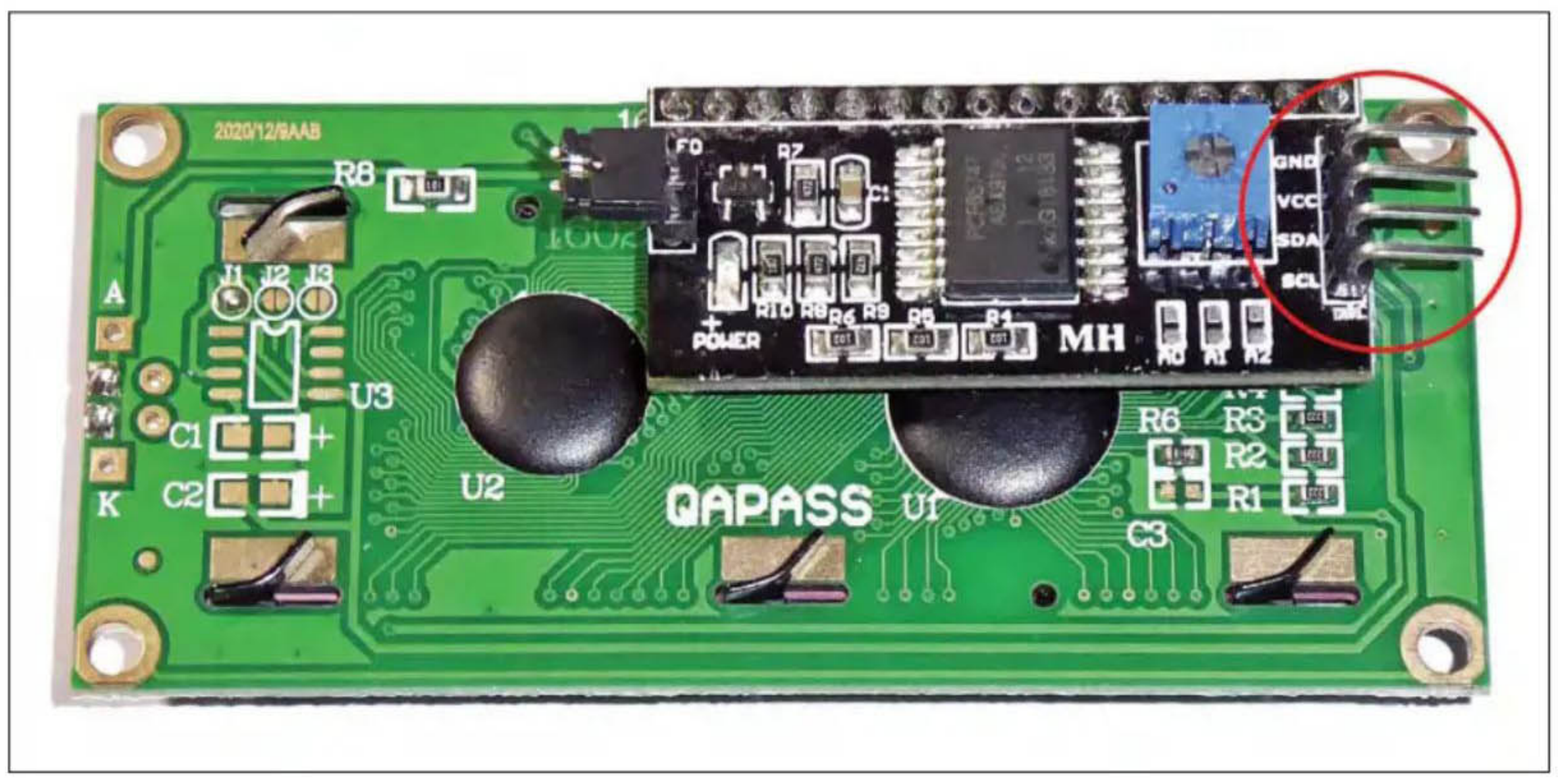


Fig.5.14. I2C interface mounted on back of a 16 × 2 LCD display.

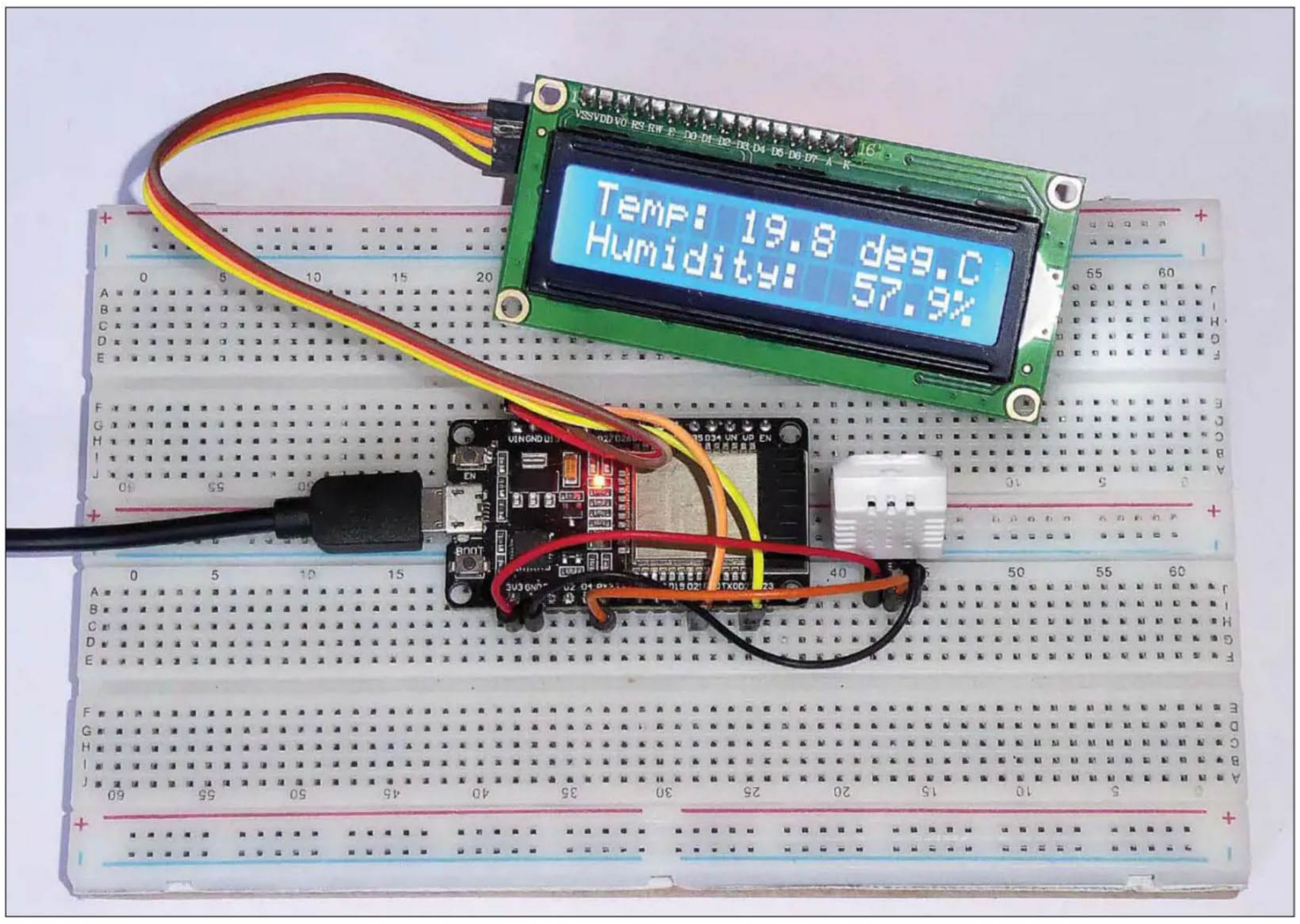
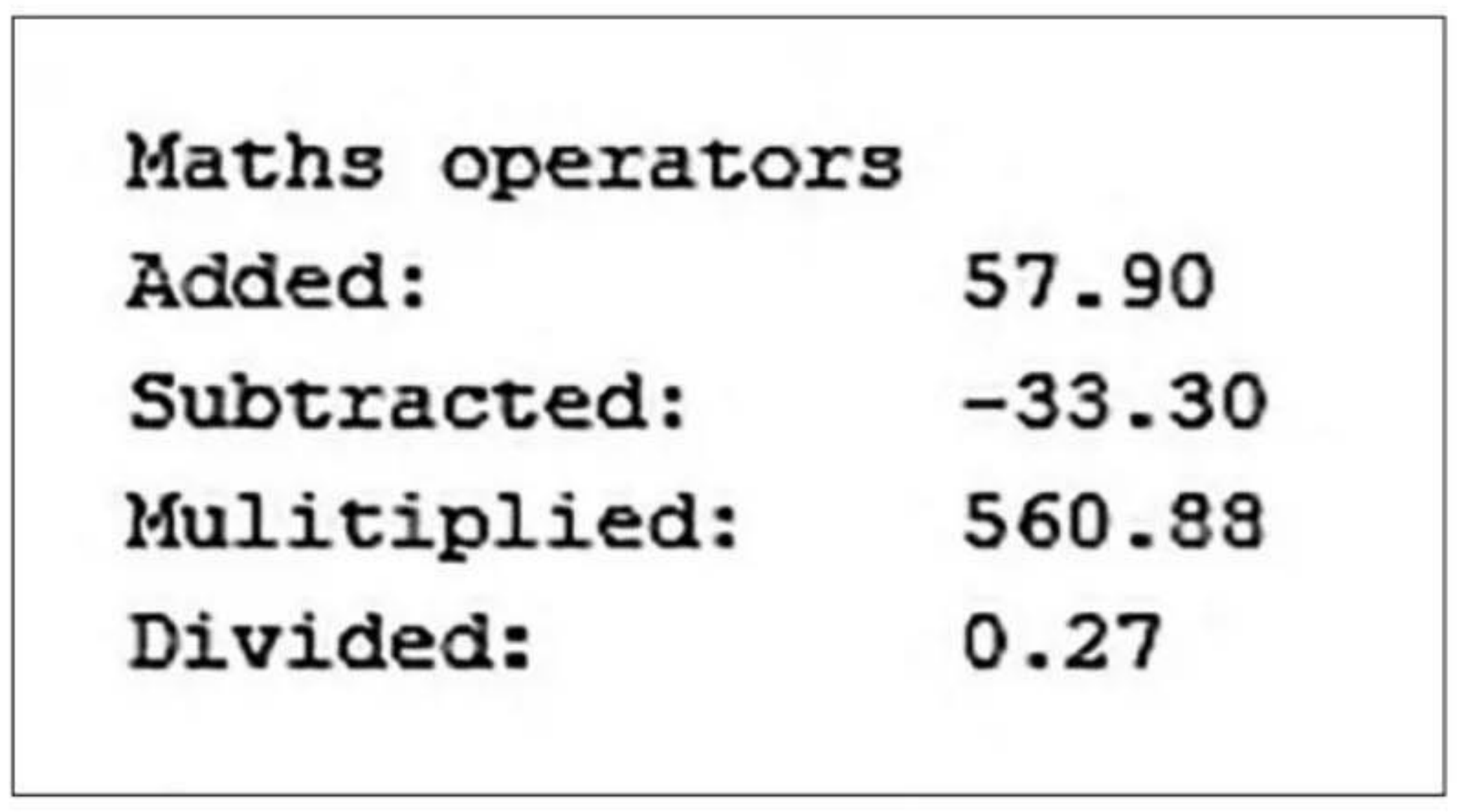


Fig.5.15. Breadboard wiring for the DHT22 and 16 × 2 LCD display.



```
Maths operators
Added:          57.90
Subtracted:     -33.30
Mulitiplied:    560.88
Divided:        0.27
```

Fig.5.16. Output from the maths operator code.

You should have already located and installed the first of these two library files. The other file can be downloaded using the IDE's Library Manager.

Coding Workshop

It's time to do some maths! You've already made use of some of the operators that the C++ language provides. They are + (addition), – (subtraction), * (multiplication), and / (division). You will doubtless already be familiar with them – but if not, Listing 5.5 shows some code that might act as a reminder.

The Serial Monitor output of Listing 5.5 is shown in Fig.5.16. The code in the main loop executes only once and halts at `while(1)` (where it waits forever). Since we don't actually need a loop that's repeated we could have simply placed all of the code in `setup()` which is only ever executed once. In this case we would simply have an empty main loop. Notice also that we've used the tab character (`\t`) to neatly space the Serial Monitor's output.

Listing 5.5 Testing the math operators

```
// Checking math operators +, -, *, and /

void setup() {
   // Start the Serial Monitor
   Serial.begin(9600);
   }

void loop() {
   float x = 12.3;
   float y = 45.6;
   Serial.println(“Maths operators!”);
   Serial.print(“Added: \t\t”);
   Serial.println(x + y);
   Serial.print(“Subtracted: \t”);
   Serial.println(x - y);
   Serial.print(“Mulitiplied: \t”);
   Serial.println(x * y);
   Serial.print(“Divided: \t”);
   Serial.println(x / y);
   while(1); // Wait forever
   }
```

As an example of using maths operators let's consider temperature conversion from Celsius to Fahrenheit. This can be easily achieved using these lines of code:

```
degF = (degC * 1.8) + 32;  // Convert deg.C to deg.F
degC = (degF - 32) / 1.8;  // Convert deg.F to deg.C
```

The variables (`degF` and `degC`) are both declared as floats, using these lines:

```
float degC;        // Temperature in deg.C
float degF;        // Temperature in deg.C
```

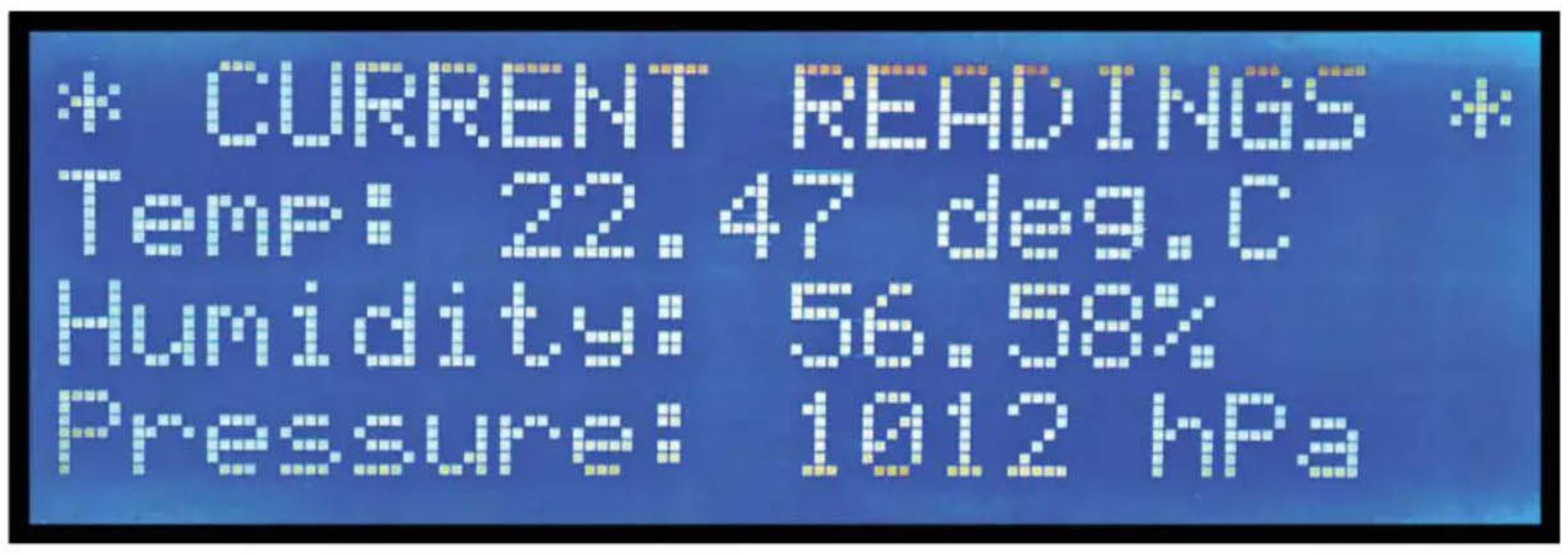
There's something vrucial to be aware of here. The order in which maths operators are applied is vitally important. The correct order of operations is brackets, orders (powers and roots), division, multiplication, addition and subtraction. You might recall this from your secondary school education as BODMA (or BOMDAS). Failing to use the correct order can produce some very odd results!

The Arduino Math library (`math.h`) includes some useful function for manipulating numbers. Note that this library is part of the language core and it does not have to be installed (unlike other library files that we've been using). Some of the most useful functions are summarised in Table 5.5.

Now let's suppose we need to determine the power present in a load resistor from a measurement of the peak

Table 5.5 Some useful maths functions from the Arduino Math library

Function	Returned value	Notation	Result (when x = 2 and y = 2)
`sqrt(x)`	square root of x	√x	1.41
`sq(x)`	square of x	x2	4.00
`pow(x, y)`	x raised to the power y	xy	4.00
`log(x)`	natural logarithm of x (base e)	ln(x)	0.69
`log10(x)`	logarithm of x (base 10)	log10(x)	0.30
`exp(x)`	e raised to the power x	ex	7.39
`sin(x)`	sine of x	sin(x)	0.91
`cos(x)`	cosine of x	cos(x)	-0.42
`tan(x)`	tangent of x	tan(x)	-2.19
`fabs(x)`	absolute value of floating point x	|x|	2
`fmod(x,y)`	floating point modulo of x divided by y	x mod y	0



```
* CURRENT READINGS *
Temp: 22.47 deg.C
Humidity: 56.58%
Pressure: 1012 hPa
```

Fig.5.17. Required display format for this month's *Teach-In Challenge*.

voltage developed across it. The relationship between RMS power, peak voltage and resistance is given by:

$P = 0.5V^2/R$

Where P is the power in the load (in watts), V is the peak voltage developed across the load (in volts), and R is the value of load resistance (in ohms). We will use floating point variable (floats) for the three variables using the following declarations:

```
float loadR, peakV, loadP;  // Declare the variables
```

We can then use the next line of code to perform the calculation:

```
loadP = (0.5 * sq(peakV)) / loadR; // Calculate the power
```

If, on the other hand, we just want to print the value returned via the Serial Monitor then we could use this line:

```
Serial.println((0.5 * sq(peakV)) / loadR);  // Print
the power
```

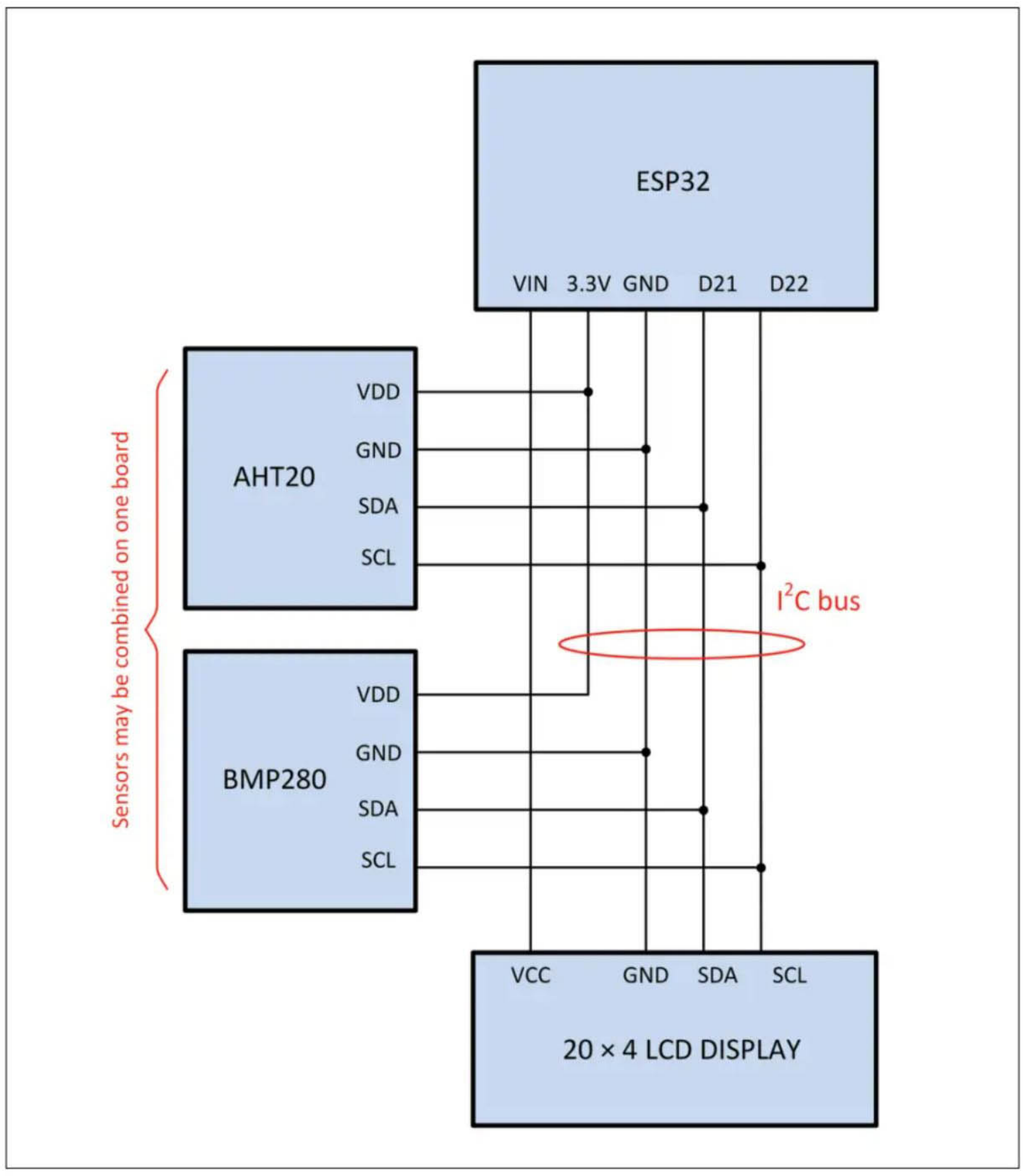


Fig.5.18. Using I2C to interconnect the sensors, 20 × 4 LCD display and ESP32.

Gotcha!

When performing calculations the order in which maths operators are applied is vitally important. It's always worth checking carefully or splitting your calculations into smaller chunks spread over several lines of code.

Listing 5.6 Initial code for this month's Teach-In challenge

```
/* ESP32 with AHT20, BMP280, and 20 x 4 LCD
displaying temperature, humidity, and pressure */

// Include the library files
#include <Wire.h>
#include <LiquidCrystal_I2C.h>
#include <AHT20.h>
#include <BMP280.h>
AHT20 aht20;
BMP280 bmp280;

// Define the LCD parameters
int lcdColumns = 20;
int lcdRows = 4;

// Setup the LCD
LiquidCrystal_I2C lcd(0x27, lcdColumns, lcdRows);

void setup() {
   Serial.begin(115200);
   Wire.begin();  // Use the I2C bus
   bmp280.begin();

   //Check if the AHT20 will acknowledge
   if (aht20.begin() == false) {
     Serial.println(“AHT20 not present!”);
     while (1)
         ;
   }
   Serial.println(“AHT20 detected!”);
   // Initialize LCD
   lcd.init();
   // Turn the backlight ‘on’
   lcd.backlight();
}

void loop() {

   // If a new measurement is available
   if (aht20.available() == true) {
     //Get the new temperature and humidity value
     float temperature = aht20.getTemperature();
     float humidity = aht20.getHumidity();
     // Get the barometric pressure
     uint32_t pressure = bmp280.getPressure();
     // Now display on the LCD
     // Your code must continue here!
```

Teach-In challenge

This month's *Teach-In challenge* involves developing a device that monitors temperature, humidity and barometric pressure, and displays the current values on a 20 × 4 LCD display

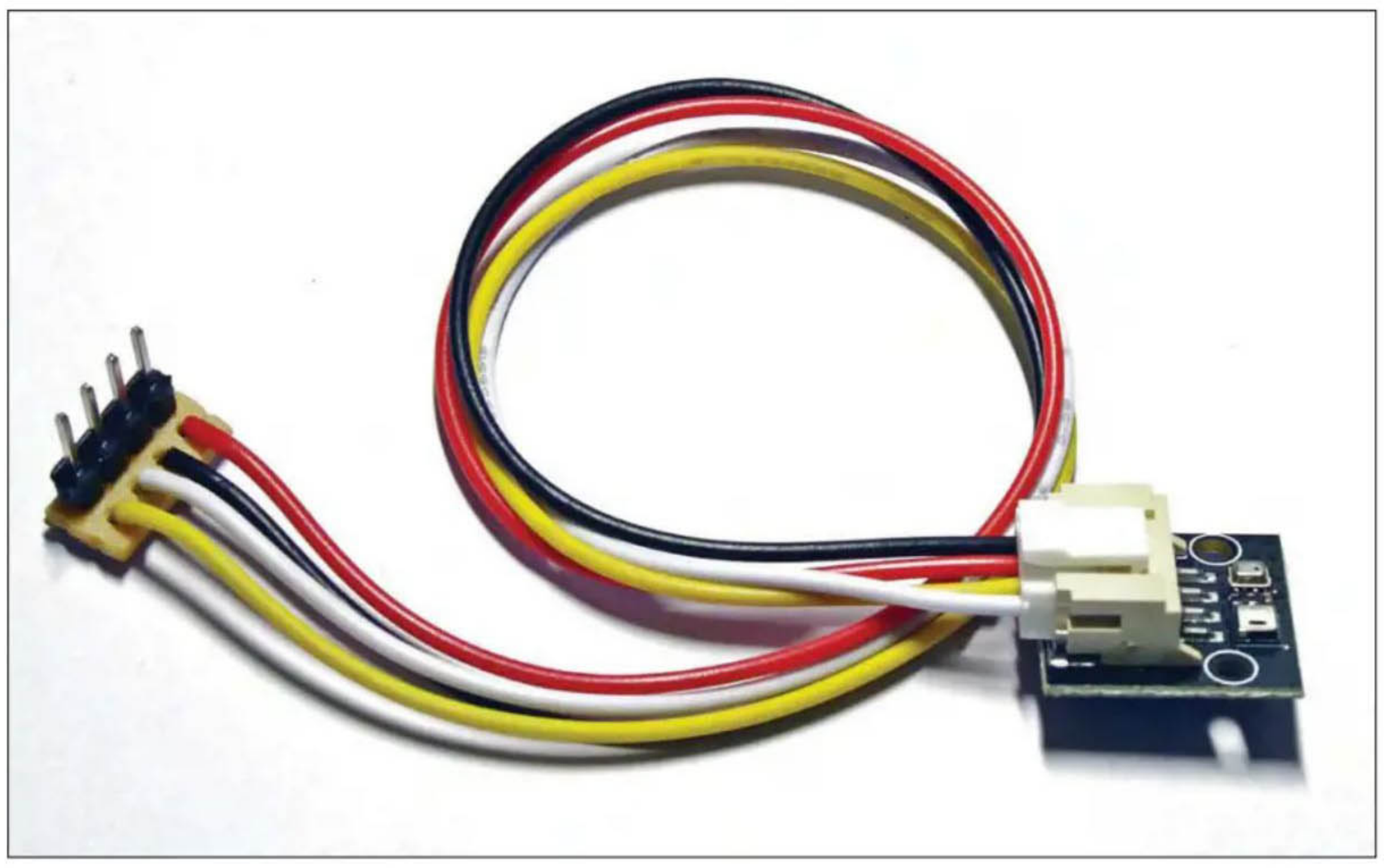


Fig.5.19. Modified AHT20/BMP280 module cable (a 4-pin header replaces one of the two connectors).

along the lines shown in Fig.5.17. We suggest that you use three I2C devices in the application: an AHT20 I2C temperature and humidity sensor, a BMP280 barometric pressure sensor, and a 20 × 4 I2C LCD display.

Using I2C, it's easy to interconnect the sensor modules, display and ESP32. In the layout shown in Fig.5.18 we've used a combined AHT20/BMP280 module. This module is available from various online suppliers and is often supplied with a 4-way cable. A simple way of attaching this to a breadboard is by removing one of the connectors and soldering a 4-pin male header mounted on a small piece of stripboard in its place (see Fig.5.19). The header can then simply be plugged into the breadboard in a suitable location (see Fig.5.20). Note that the colours used for the combined sensor module are not the same as those shown for the breadboard wiring in Fig.5.19. Additional wiring will be needed is you are using separate AHT20 and BMP280 sensors.

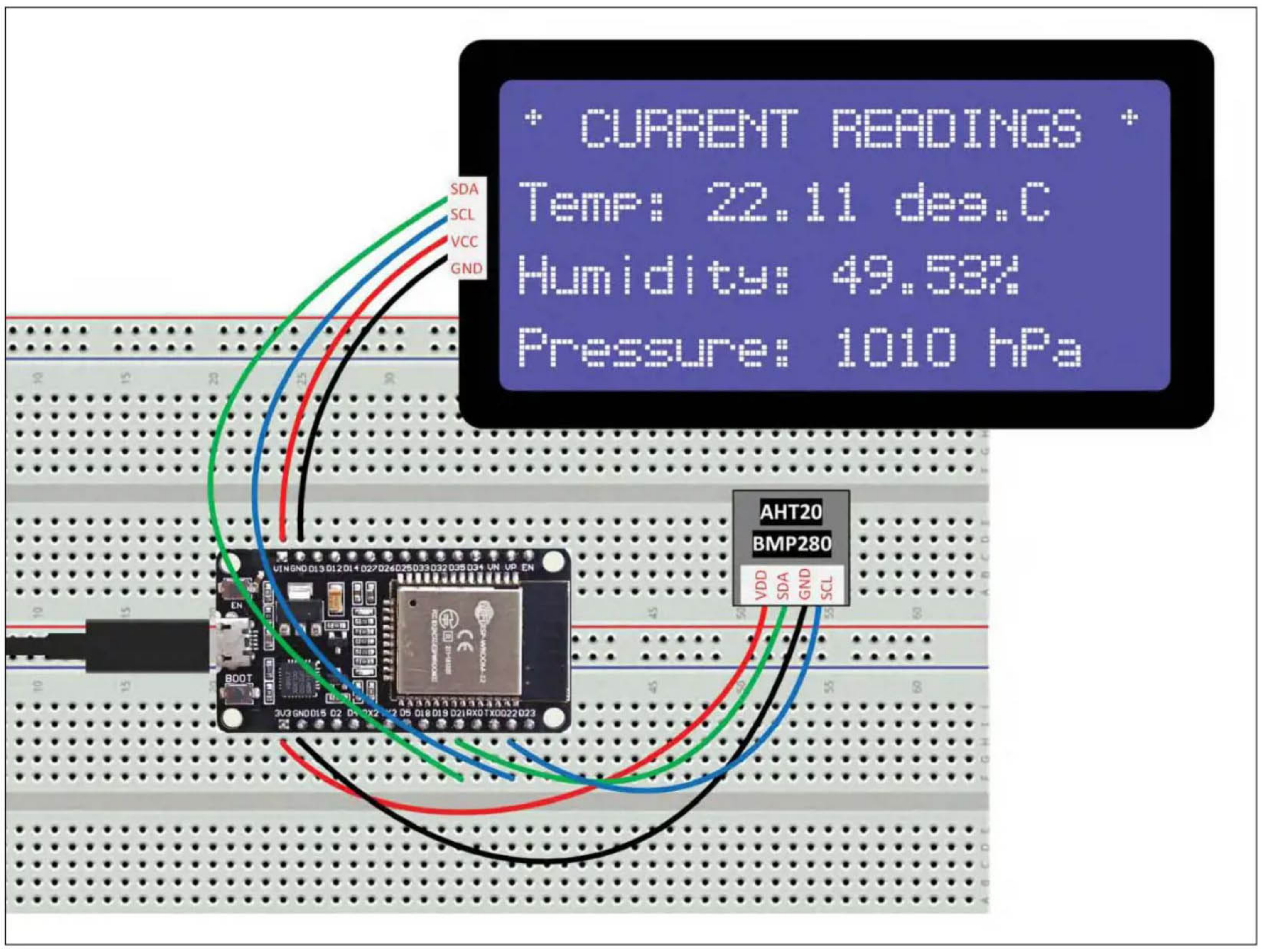


Fig.5.20. Wiring diagram for this month's *Teach-In Challenge*. Note that the combined sensor module cable is not shown in this diagram.

In this challenge we're going to leave you to develop the code, but we've provided you with some initial lines in Listing 5.6. The next task is completing the code in the main loop. This should send the temperature, humidity and pressure data to the LCD panel. If you get stuck, you can always download a solution from the *PE* website. Good luck!

Next month

In *Part 6*, we will be showing you how to connect your ESP32 to a Wi-Fi network. *Coding Workshop* will deal with strings and string manipulation and our *Practical Project* will feature a network-connected temperature and humidity monitor. Finally, as we will have reached the half-way point in our series, *Checkpoint* will provide you with a means of testing your ESP32 knowledge!

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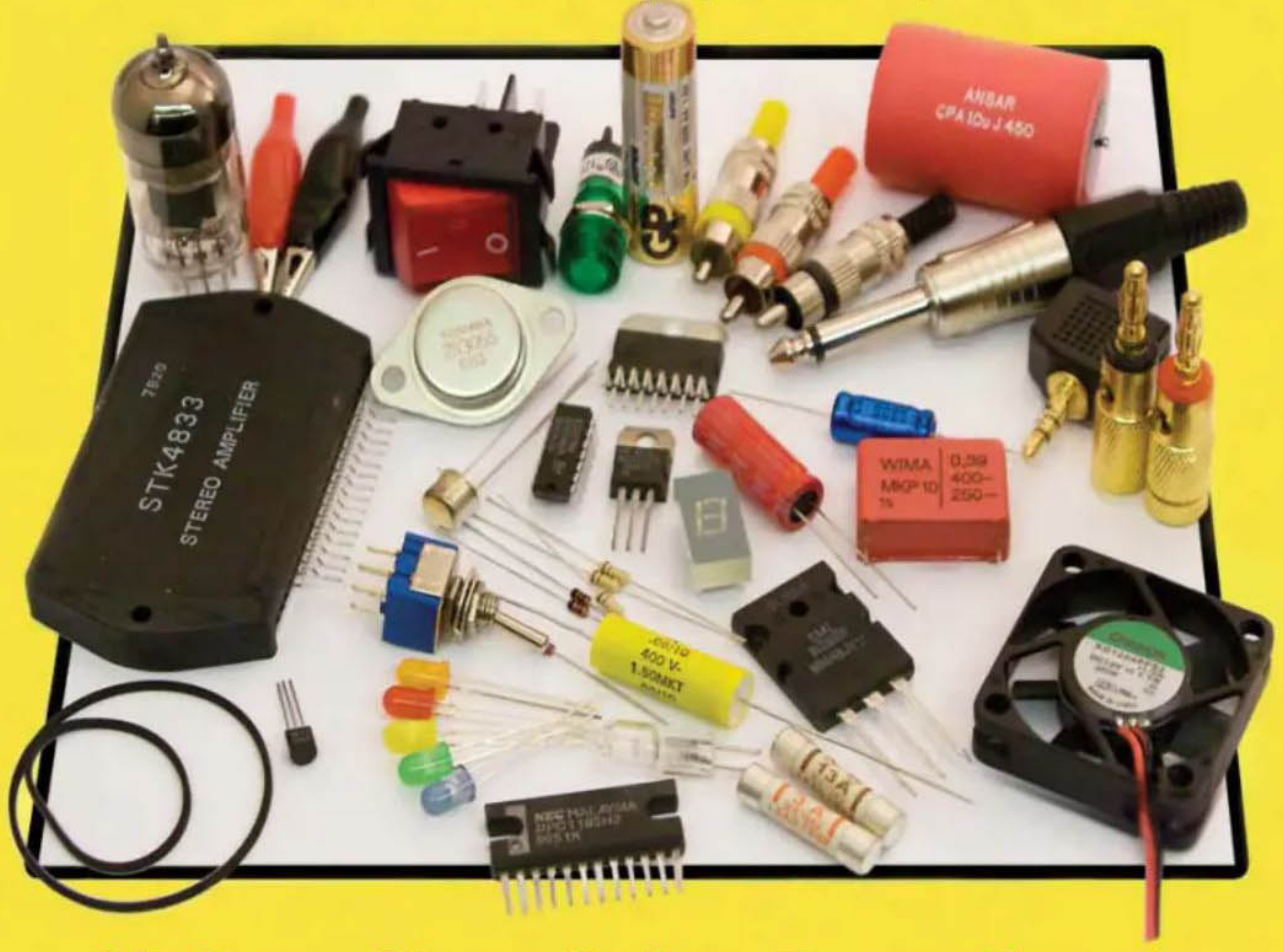

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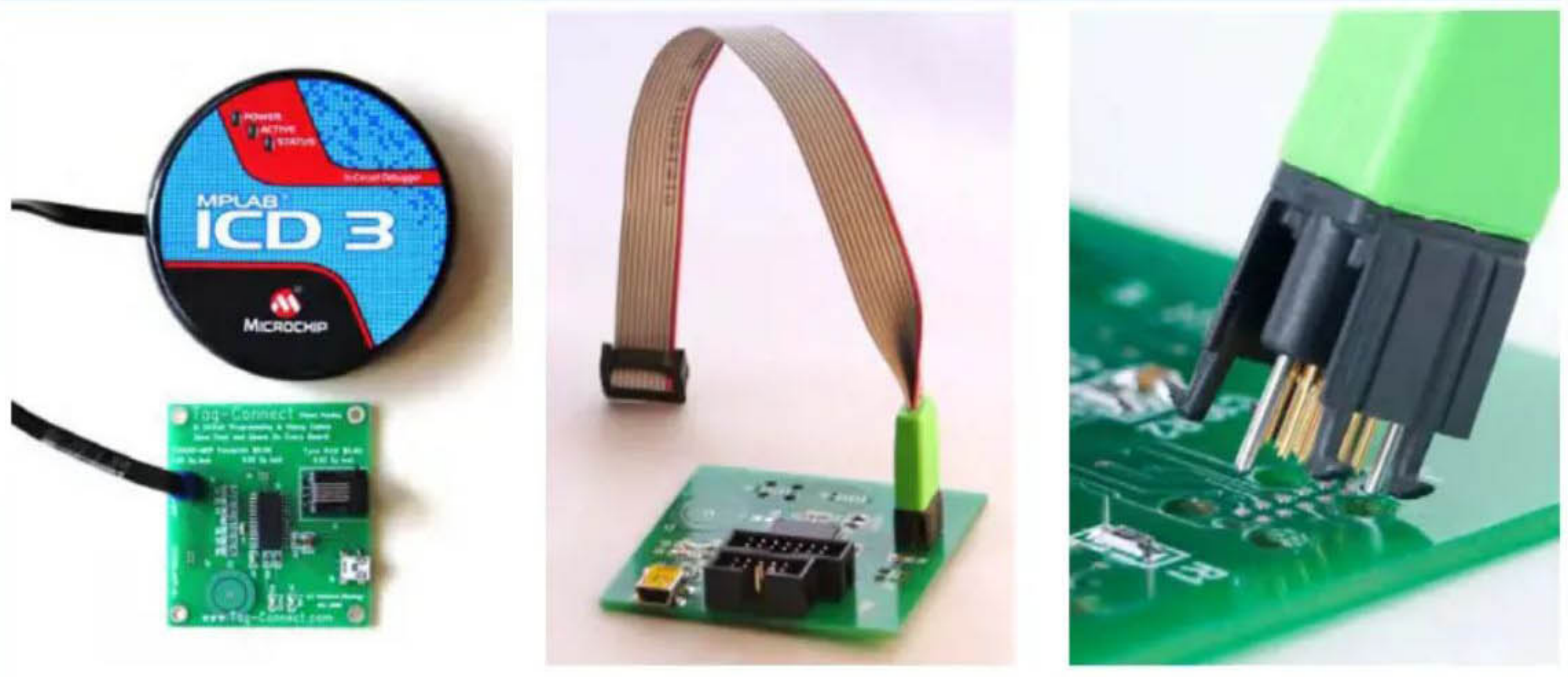

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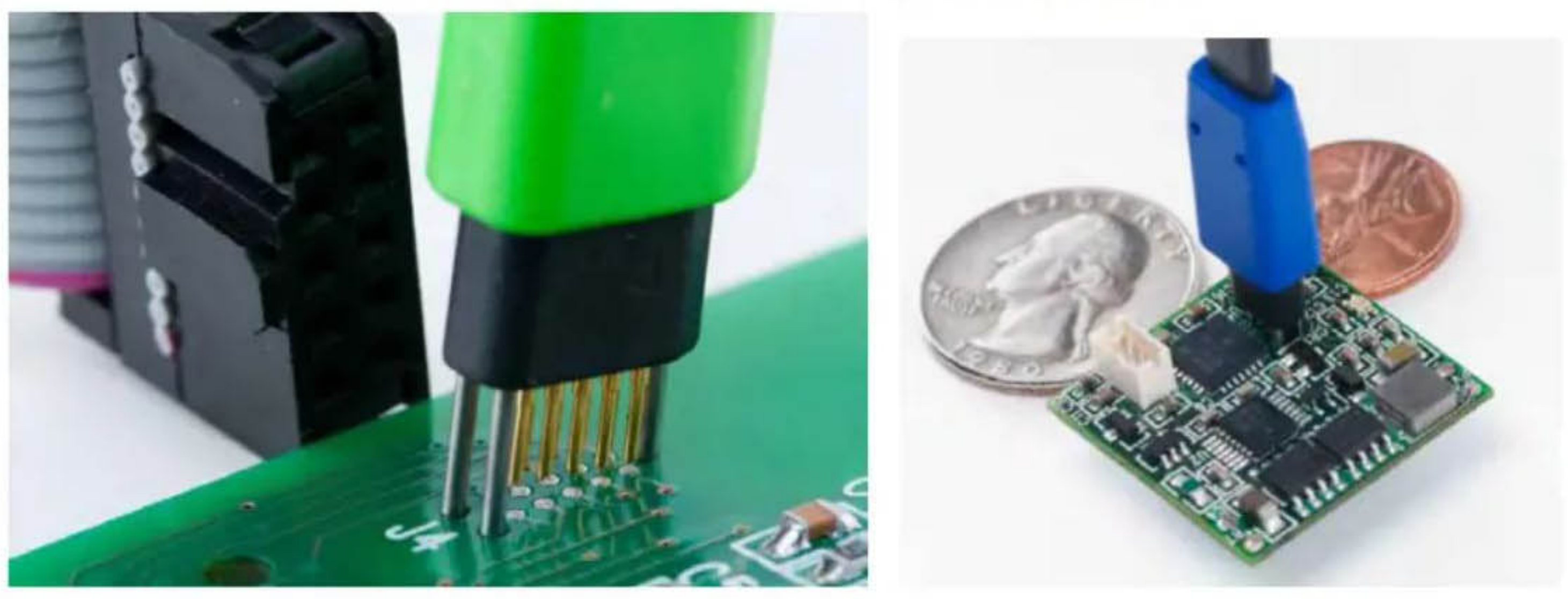

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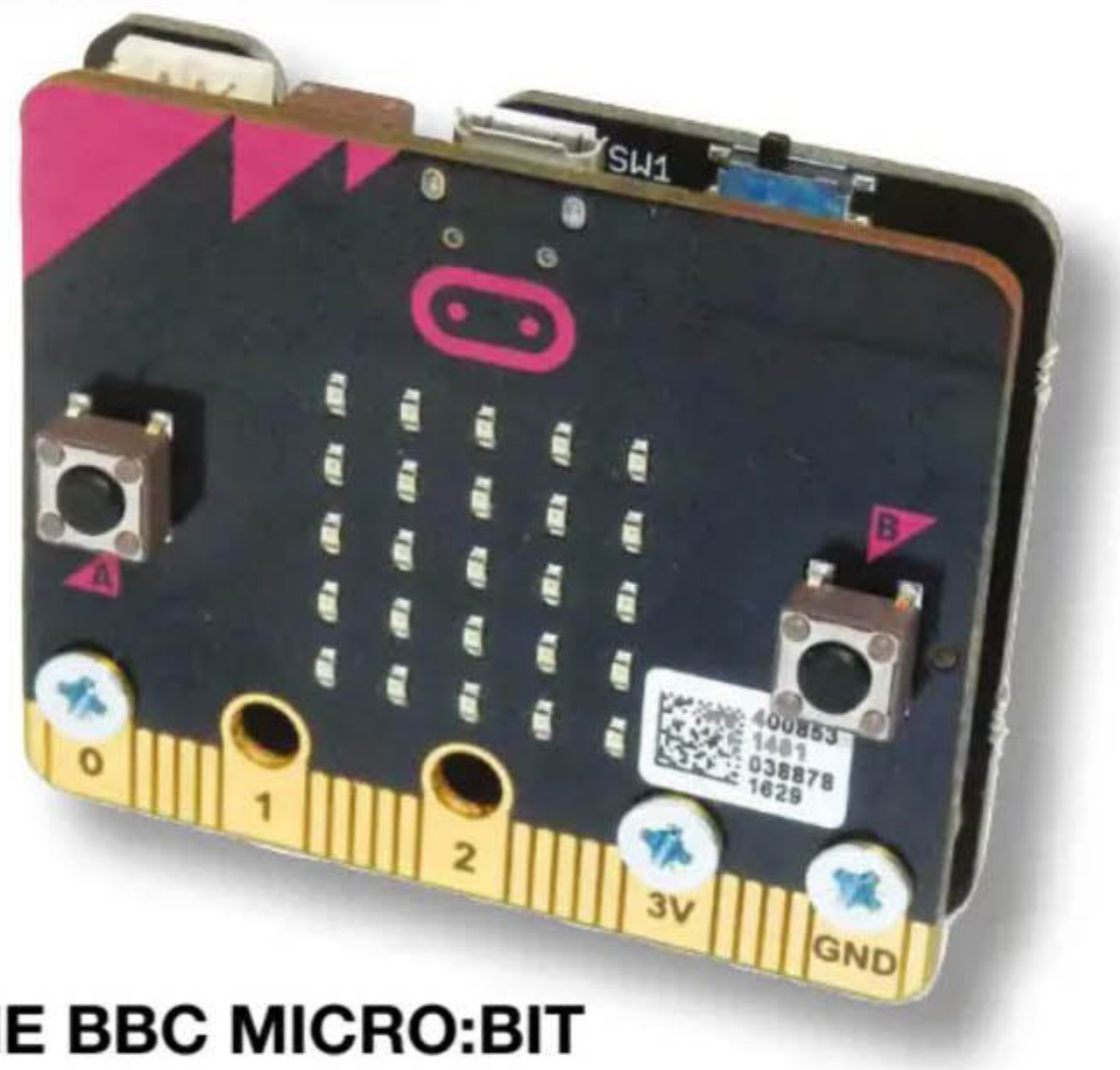

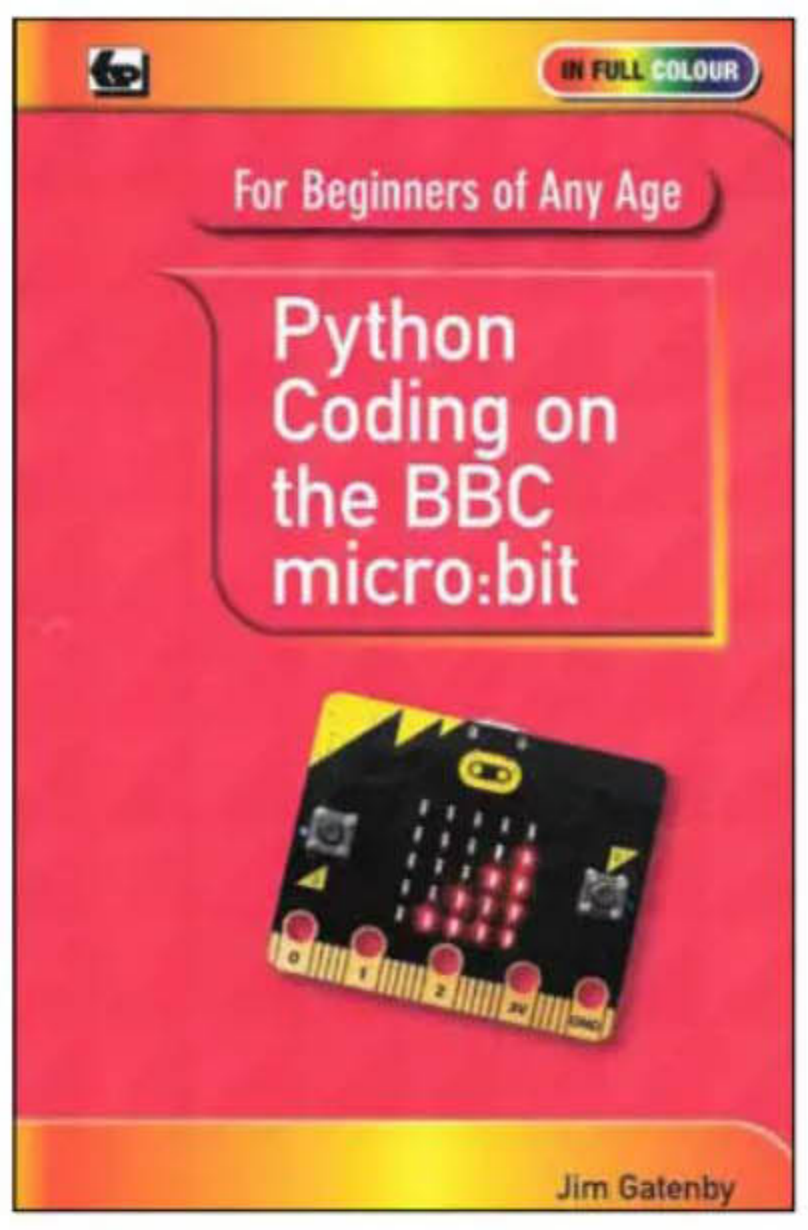

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Jim Gatenby

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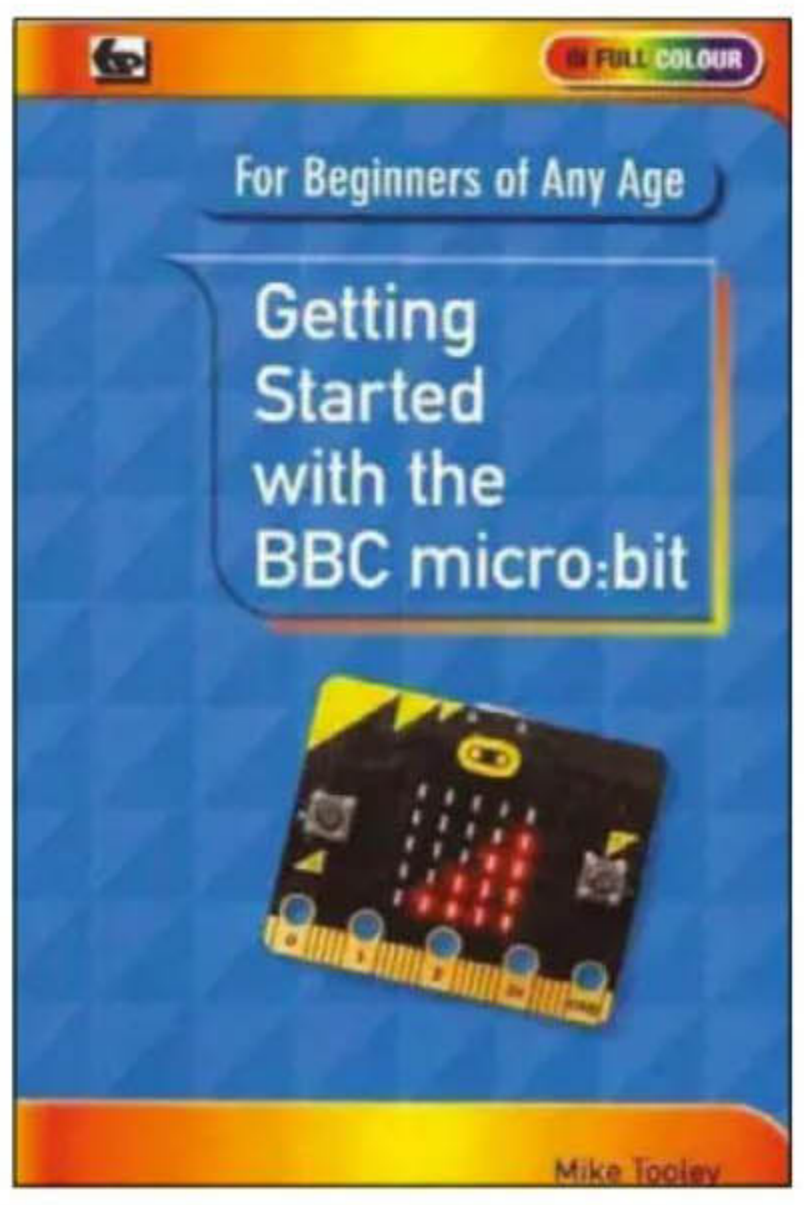

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Mike Tooley

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DSP Active Crossover (LCD)	01106196	
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AUGUST 2019		
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JULY 2019		
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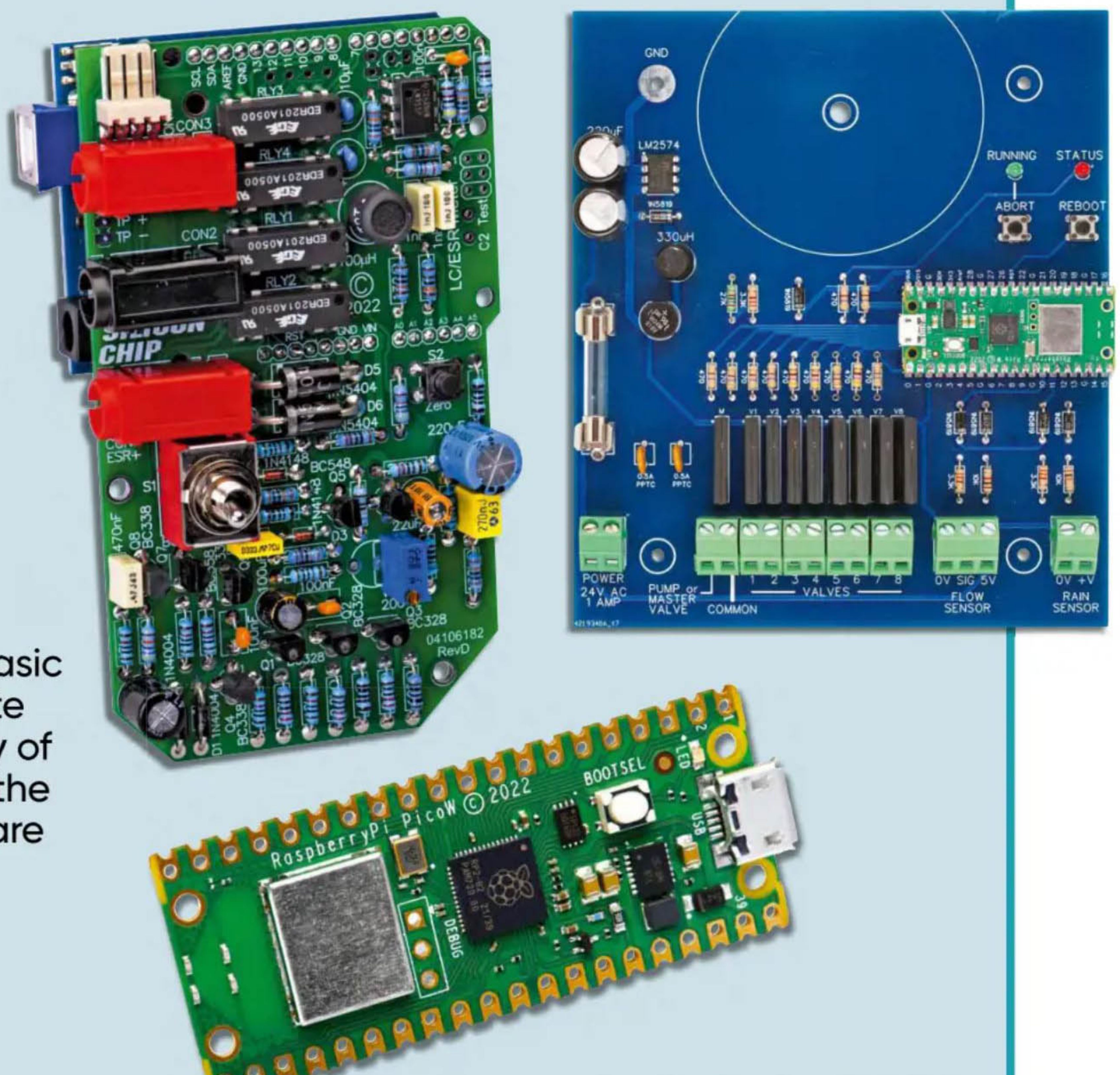
Next Month – in the August issue



Arduino-Based LC and ESR Meter

This enhancement to our Wide-Range Digital LC Meter (June 2019) allows it also to measure capacitor ESR. That is extremely useful for diagnosing faulty equipment because increasing ESR over time is one of the most common ways electrolytic capacitors fail.

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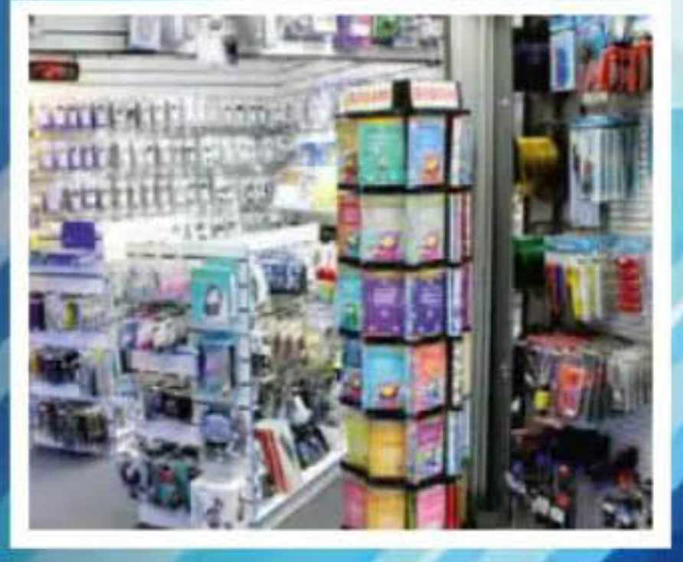

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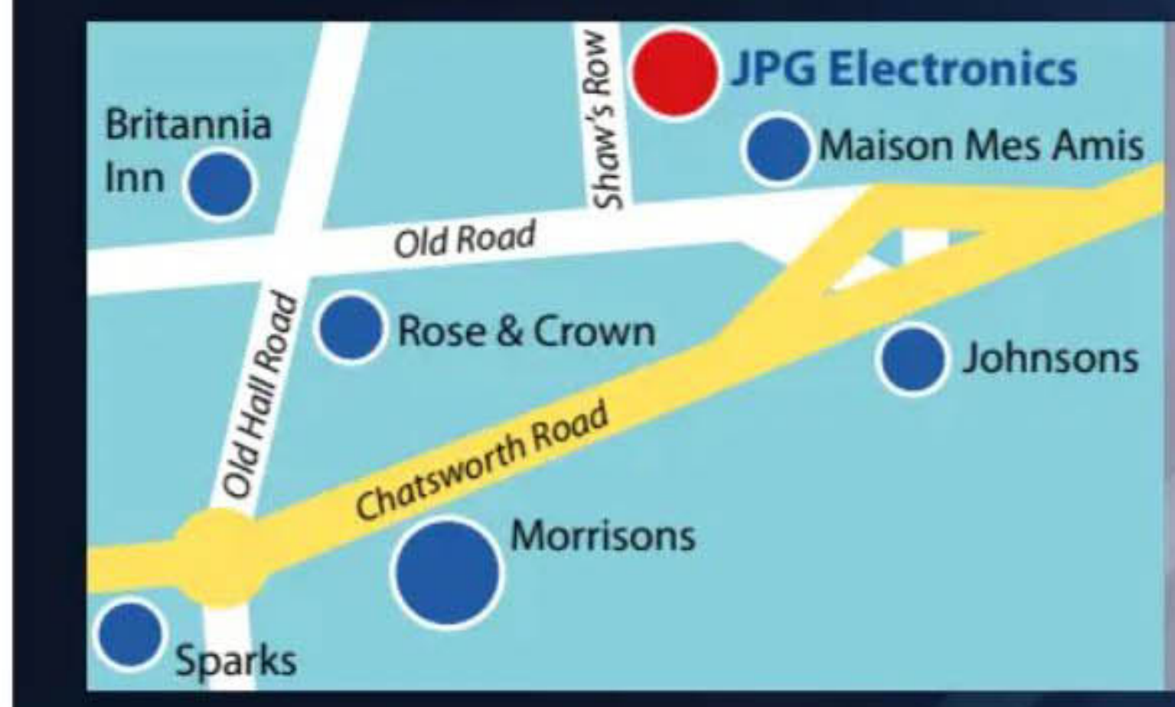

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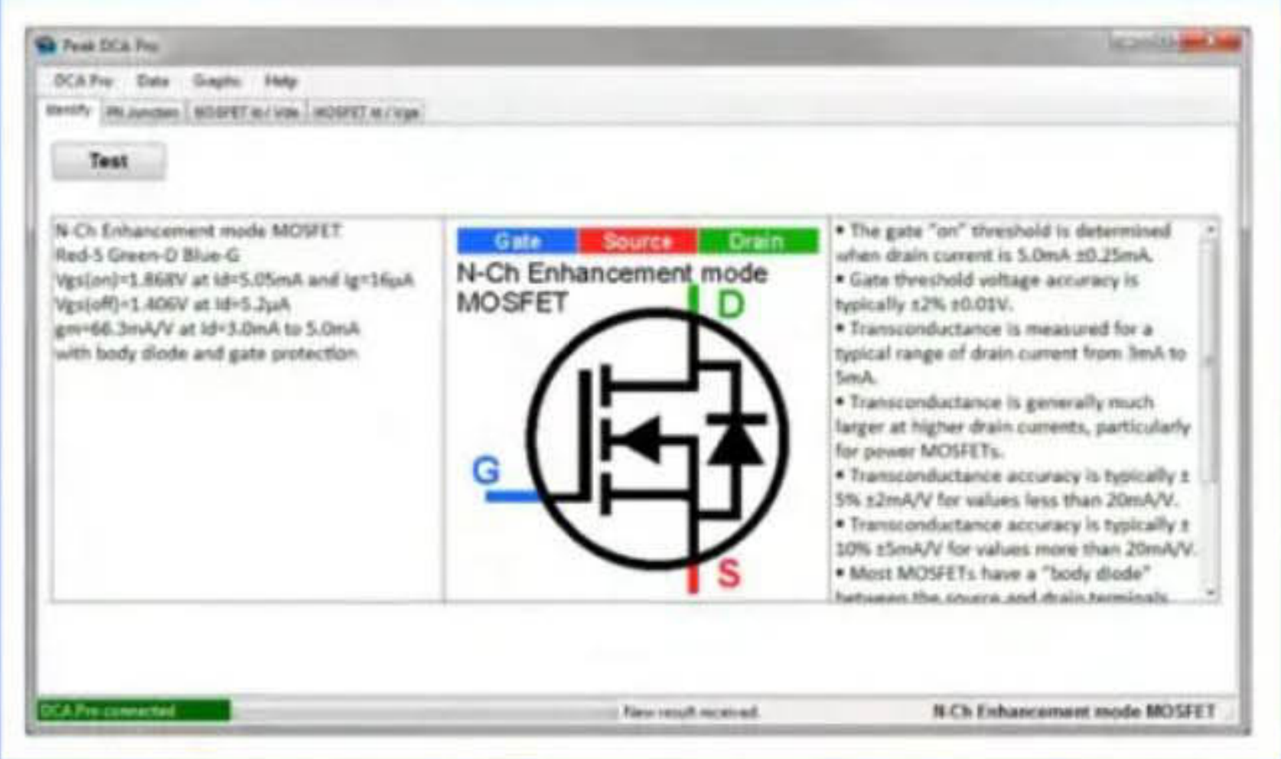
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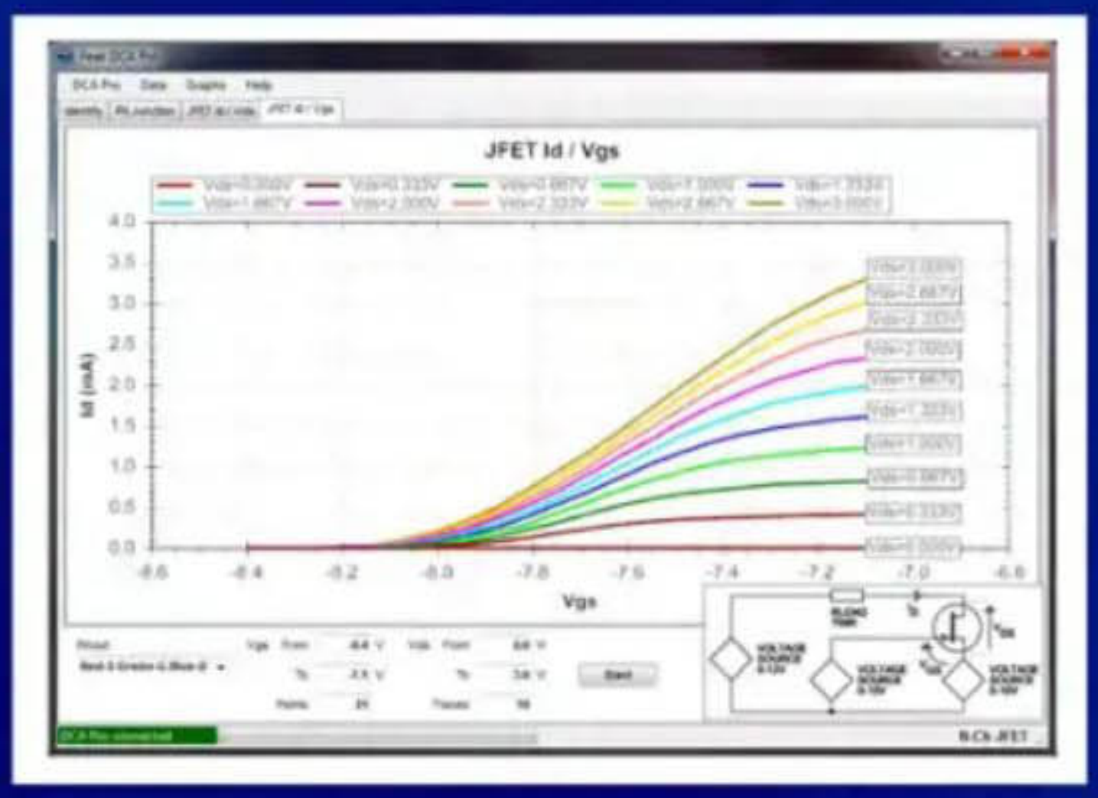
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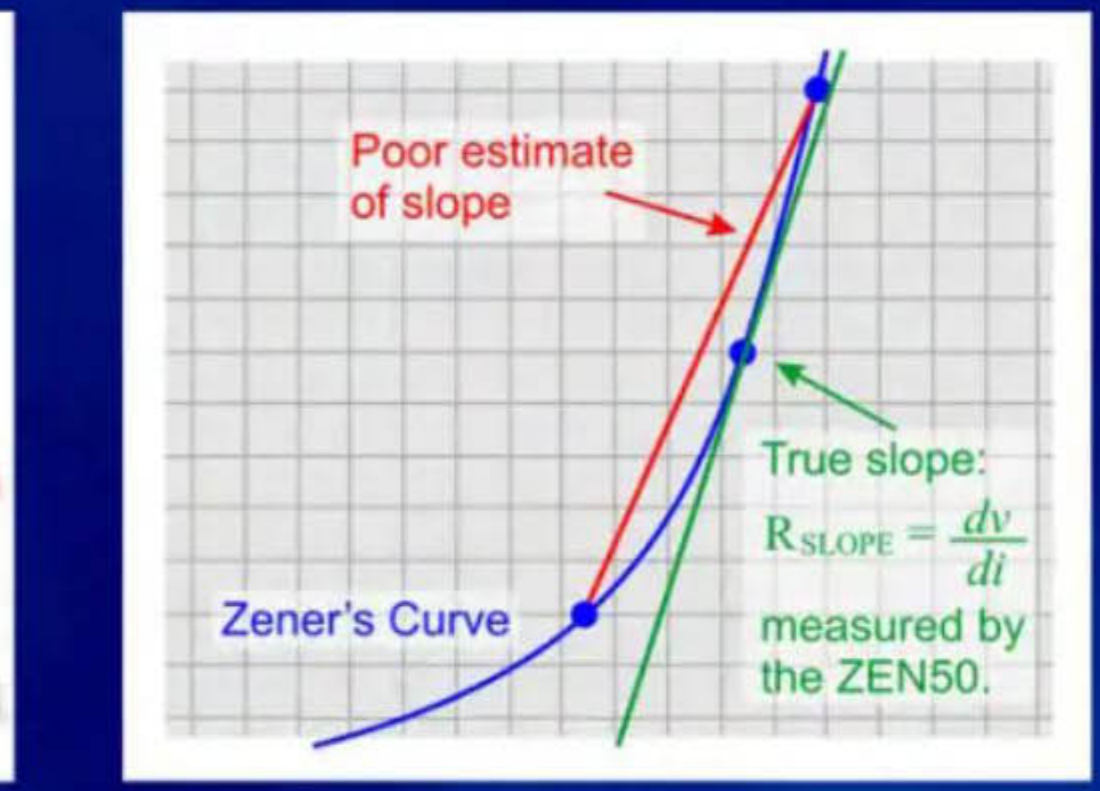

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